ECONOMIC GEOLOGY

WITH WHICH IS INCORPORATED

THE AMERICAN GEOLOGIST

VOL. XI DECEMBER, 1916 No. 8

THE PHYSIOGRAPHIC CONDITIONS AT BUTTE, MONTANA, AND BINGHAM CANYON, UTAH, WHEN THE COPPER ORES IN THESE DISTRICTS WERE ENRICHED.[1]

WALLACE W. ATWOOD.

CONTENTS.

	PAGE.
Introduction	698
Acknowledgments	700
Location and Extent of Area	701
Geographic Features	701
Analysis of the Topography	101
Drainage	703
General Geologic Conditions	704
Physiographic History	706
General Outline	706
Pre-peneplain Stage	707
Summit Peneplain	707
First Cycle of Erosion	707
Uplift and Deformation of Peneplain	708
Opening of Second Cycle of Erosion	708
Closing of Drainage	711
Third Cycle of Erosion	711
Renewal of Mountain Growth	714
Piracy of the Missouri and Opening of Drainage	714
Fourth Cycle of Erosion	714
Glaciation	717
Pre-Wisconsin Stage	717
Later or Wisconsin Stage	720
The "Flat" at Butte	720
Secondary Enrichment of the Ores	721

[1] A Shaler Memorial Investigation.

PAGE.
During the First Cycle of Erosion 721
During the Second Cycle of Erosion 723
During the Third or Cycle of Closed Drainage 724
During the Fourth Cycle of Erosion 727
Conclusion 727

PART II. THE BINGHAM CANYON DISTRICT.
Introduction 732
General Geology 734
Physiography 735
Bingham Canyon Ores 738
Relation of Physiographic Development to the Enrichment of the Ores .. 738

PART I. THE BUTTE DISTRICT.

PART I. THE BUTTE DISTRICT.

INTRODUCTION.

Careful studies of the physiographic evolution of certain of the mountain ranges in the western part of the continent have brought out the history of several cycles of erosion in each of the areas studied. Various investigations of the great mineral deposits in these same regions have shown that many of the ore bodies, and especially the copper ores, have been secondarily enriched by descending waters. The evolution of the surface and the secondary enrichment of the ores have probably been in progress at the same time, and since the position and movements of the ground waters are dependent chiefly upon surface relief and climatic conditions, it is apparent that there is an important relationship between these two lines of scientific investigation.

While a land mass is being dissected, the ground-water table conforms roughly to the topography, but without sharp accentuations which may characterize the surface features. In general the water table will be farther below the surface in the hills than in the lowlands, and will come to the surface along the channels of the permanent streams. As the land mass is eroded the ground-water table is lowered in that mass, until at the peneplain and base-level stages, the ground-water table remains almost stationary for long periods of time. During successive cycles of erosion the position of the base-level of erosion in the land mass being

dissected must change, and if climatic conditions remain constant, such changes are necessarily accompanied by changes in the position of the ground-water table. If the land mass is elevated, the base-level will be lowered through the land, and the ground-water table will be slowly lowered.

When a land mass is depressed, the base-level of erosion and the ground-water table are elevated throughout that land mass. Moist climates will raise the ground-water table, and dry periods lower that table. The movements of the ground waters would depend in part upon the permeability of the rocks and upon surface relief, but the general statement will remain true that the ground-water table when established will conform in a general way to the topography.

As the ground-water table is raised or lowered, the zones in which the chemical changes associated with the secondary alteration of ore deposits take place are varied in thickness. It is therefore evident that there must be a very important relationship between the evolution of the surface and the secondary alterations of ore deposits. The careful study of the secondary ores of a chosen area may yield important suggestions to those interpreting the surface, and, in turn, the history of the surface changes must certainly prove of value to those working out the full geologic history of the secondary ores.

Mr. L. C. Graton and his associates, while engaged in an exhaustive investigation of the secondary enrichment of copper ores, have appreciated from their line of attack that an understanding of surface changes in the vicinity of the great mining camps is of real significance to them in understanding the location and extent of the secondary ores, and that the geologic history of those secondary ores could not be worked out completely without an appreciation of the physiographic history of the area under study.

Mr. W. H. Emmons, in a paper on the "Enrichment of Sulphide Ores,"[2] outlined somewhat fully the physical conditions which must affect the processes of enrichment. It is clear from his paper that he appreciated the significance of physiographic

[2] Emmons, W. H., "The Enrichment of Sulphide Ores," U. S. Geol. Survey, Bull. 529, 1913.

studies in association with the study of the history of secondary ores. Mr. J. M. Boutwell[3] and many other recent writers on ore deposits have expressed the hope that detailed physiographic studies might be carried out in the regions of the great secondary ore deposits.

The possibility of important results coming from such investigations as are herein described, was, therefore, anticipated by men working in very different fields of geological research.

ACKNOWLEDGMENTS.

I wish to acknowledge the cordial support which my colleagues at Harvard University have given to this investigation, and especially to L. C. Graton, who has in many ways assisted in the prosecution of the work. Mr. E. H. Perry joined me for several weeks in the field, and to him I am indebted for immediate counsel, especially regarding the underground conditions in the various mines scattered through the Butte district. While engaged in work at and about Butte, the officers of the several mining companies extended many courtesies to me, and any assistance which was asked. D. C. Bard, Reno H. Sales, Paul Billingsley, C. H. Bowman and several others gave freely of their time, and in many ways assisted me in the investigation. I recall with a great deal of pleasure several days in the field with those who have just been mentioned.

W. H. Weed's paper on the "Geology and Ore Deposits of the Butte District"[4] was the best guide to the local geology, and Sales's paper on the Butte ores[5] was the chief published source of information regarding underground conditions. The published report of Emmons and Calkins[6] on the Phillipsburg quadrangle,

[3] Boutwell, J. M., "Economic Geology of the Bingham Mining District, Utah," U. S. Geol. Survey, Prof. Paper 38, 1905.

[4] Weed, W. H., "Geology and Ore Deposits of the Butte District, Montana," U. S. Geol. Survey, Prof. Paper 74, 1912.

[5] Sales, R. H., "Ore Deposits at Butte, Montana," *Am. Inst. Min. Eng. Trans.*, vol. 46, 1913.

[6] Emmons, W. H., and Calkins, F. C., "Geology and Ore Deposits of the Phillipsburg Quadrangle, Montana," U. S. Geol. Survey, Prof. Paper 78, 1913.

PLATE XXVI

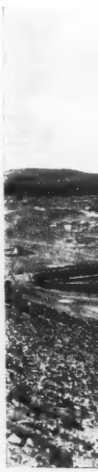


PLATE XXVI.

Walkerville.

Anaconda Hill in middle ground with many surface pla

Columbia Gardens near base of East Ridge.

East Ridge forms the Sky Li

ny surface plants of the large mines.

Panoramic view of Butte, Mont., looking east from Big Butte.

ast Ridge forms the Sky Line.

The "Flat" in middle ground.

Timber Butte and intermediate or bench level; in middle ground Montana State School of Mines.

and Lindgren's work on the Bitterroot Range[7] were of immediate value in connection with the field work. So also were the reports by Mr. Pardee[8] and Mr. Douglass.[9]

LOCATION AND EXTENT OF AREA.

The investigation was to center upon the Butte mining district, which is located in southwestern Montana, but after a few days of study of the physiographic conditions at and immediately surrounding Butte (see Plate XXVI.), it was apparent that a much larger area must be examined before any conclusion could be safely reached as to the chief events in the physiographic history of the district. The studies were therefore extended by a series of excursions to the northeast as far as Great Falls, eastward to the vicinity of Three Forks, southward beyond the Continental Divide and state boundary into Idaho, and even to Gilmore and the Lemhi Range and upper Salmon River country of northeastern Idaho. This particular region was visited because of the studies of Dr. Umpleby.[10] This was the nearest region to Butte where the physiographic history had been worked out in detail. To the northwest the field observations were extended through the Deer Lodge Valley to Helmville, Drummond, and Phillipsburg. The area examined includes about 20,000 square miles. (See Plate XXVII.)

GEOGRAPHIC FEATURES.

ANALYSIS OF THE TOPOGRAPHY.

The larger geographic features of southwestern Montana and northeastern Idaho include: (1) The western margin of the Great

[7] Lindgren, Waldemar, "A Geologic Reconnaissance Across the Bitterroot and Clearwater Mountains in Montana and Idaho," U. S. Geol. Survey, Prof. Paper 27, 1904.

[8] Pardee, J. T., "Coal in the Tertiary Lake Beds of Southwestern Montana," U. S. Geol. Survey, Bull. 531, pt. 2, pp. 229–244, 1913.

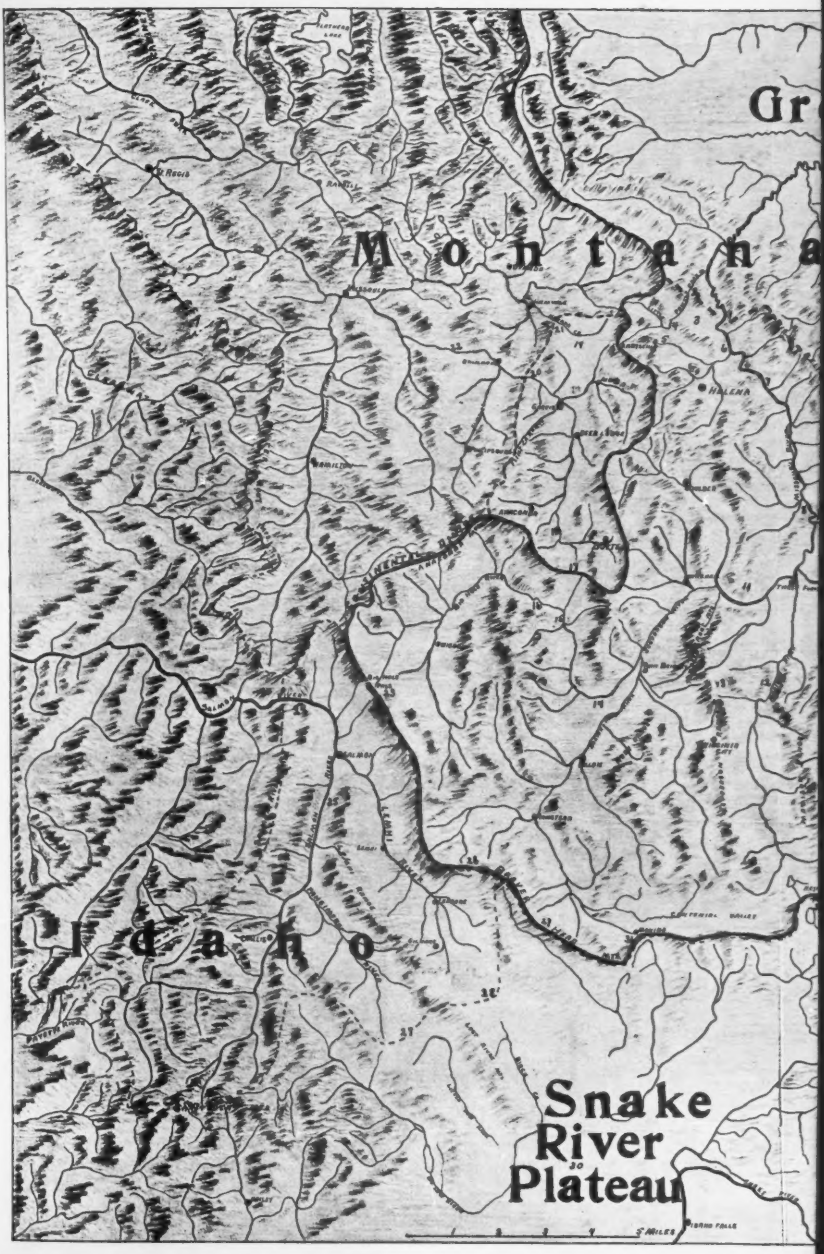
[9] Douglass, Earl, "The Tertiary of Montana," *Carnegie Mus. Mem.*, vol. 2, no. 5, pp. 203–223, 1905.

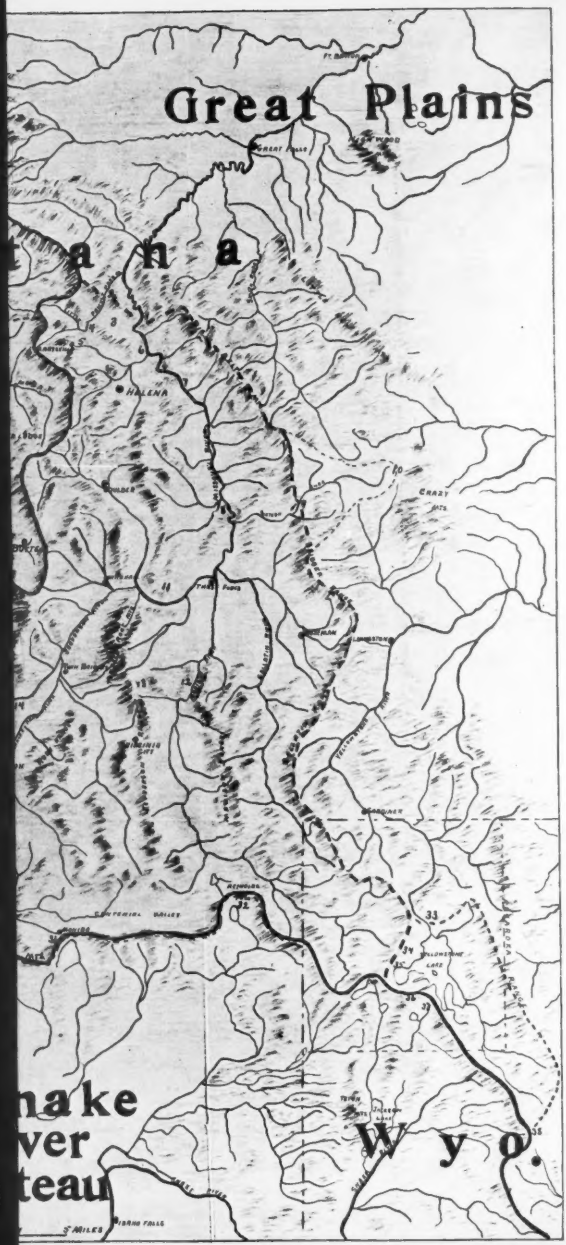
[10] Umpleby, J. B., "The Old Erosion Surface in Idaho," *Jour. Geology*, vol. 21, no. 3, pp. 224–231, 1913. "An Old Erosion Surface in Idaho: Its Age and Value as a Datum Plane," *Jour. Geology*, vol. 20, no. 2, pp. 139–147, 1912. "Geology and Ore Deposits of Lemhi County, Idaho," U. S. Geol. Survey, Bull. 528, 1913.

EXPLANATION OF PLATE XXVII.

Relief map of southwestern Montana and portions of Idaho and Wyoming, including the area under consideration in the physiographic studies of the Butte district. Heavy solid line shows present position of Continental Divide. Heavy dash line shows a former position of Continental Divide. Light dash line northwest of Butte bounds an area captured by Clark Fork of the Columbia River; that in Idaho, an area captured by the Salmon River; that in Yellowstone Park, an area captured by the Yellowstone River.

Localities at which drainage conditions demand special explanations: (1) Canyon of the Missouri where piracy occurred; (2) first piracy of Little Prickly Pear Creek; (3) divide in old stream course; (4) second piracy of Little Prickly Pear Creek; (5) divide in old stream course; (6) gorge due to superposition; (7) gorge due to superposition; (8) gorge due to superposition; (9) probable head of Sixteen-mile River before piracy of the Missouri occurred; (10) present head of Sixteen-mile River; (11) gorge due to superposition; (12) gorge probably due to superposition; (13) abandoned stream course; (14) gorge due to superposition; (15) gorge due to superposition; (16) piracy resulting in capture of Big Hole River; (17) divide in old stream course; (18) gorge due to superposition; (19) divide in old stream course; (20) piracy of Hell Gate River; (21) piracy of Nevada Creek; (22) probable piracy of Hell Gate River; (23) Big Hole Pass, a wind gap; (24) canyon of Salmon River, near point where piracy occurred; (25) piracy resulting in capture of the Lemhi and Pahsimeroi Rivers; (26) wind gap northeast of Leadore; (27) small wind gap; (28) divide in old stream course; (29) divide in old stream course; (30) probable former route of drainage to Snake River; (31) pass at Monida, a wind gap; (32) Reynolds Pass, a wind gap; (33) canyon of the Yellowstone where piracy occurred, with capture of Yellowstone Lake and headwaters of Snake River; (34) wind gap; (35) wind gap; (36) wind gap; (37) Two Ocean Pass, a wind gap; (38) junction of former with present Continental Divide.


Gr
Montana
Idaho
Snake
River
Plateau


Great Plains
a n a
HELENA
CRAZY
ake
ver
teau
W y o.

Plains; (2) a series of mountain ranges, most of which have north-south axes; (3) broad open intermontane troughs; (4) the northeastern margin of the Snake River Plateau. These features are shown on Plate XXVII.

In a more detailed analysis of the topography mention would be made of certain mountain centers such as the Highwood and Crazy Mountains near the western margin of the Great Plains, of the Anaconda and Beaverhead Ranges, which extend in a more east-west direction than the other ranges in the region, of the adjoining lava plateau in the Yellowstone National Park, the canyon of the Yellowstone River, the canyon of the Missouri River northeast from Helena, the gorge of the Big Hole River, the narrows in the Missouri River Valley west of Three Forks, the Madison River Canyon, the Salmon River Canyon, and the somewhat special lowland area near Butte which is locally known as the "Flat."

DRAINAGE.

Most of the area under consideration is drained by the headwaters of the Missouri River, but the immediate district about Butte drains into the Clark Fork of the Columbia, and thence to the Pacific Ocean. At the southwest, beyond the Beaverhead Range, the drainage is in part into the Snake River, and in part into the Salmon River which soon joins the Snake River, and, in time, the Columbia.

The drainage conditions within the area are however, exceedingly peculiar. The larger streams, for the most part, follow the great intermontane troughs, but after following one of these broad open valleys for a distance, they, in many instances, enter sharp, narrow gorges. There are places where the Big Hole, Jefferson and Missouri Rivers have cut sharp canyons in very resistant rock at short distances to one side of areas of unconsolidated sands and gravels. (See nos. 8, 11, 14, 15, Plate XXVII., and Fig. 52.) Many old valleys have evidently been abandoned. There are divides in the great intermontane valleys, indicating that the drainage which once followed such a valley has been parted and forced to flow into two distinct systems. At a point just southwest of Butte (no. 17, Plate XXVII., and Fig. 52)

such a division of the drainage has caused a portion of the water to flow northward into the Columbia River, and the rest southward to join, in time, the Missouri River. Along the Continental Divide at Big Hole Pass (no. 23, Plate XXVII., and Fig. 52), at the pass northeast of Leadore (no. 26, Plate XXVII., and Fig. 52), near Monida (no. 31, Plate XXVII., and Fig. 52), and at Reynolds Pass (no. 32, Plate XXVII., and Fig. 52) there is evidence of old stream courses which have been abandoned. These passes are great wind gaps. Still farther to the southeast in Yellowstone Park are the passes in the former and present Continental Divide (nos. 33, 34, 35, 36, 37, Plate XXVII., and Fig. 52) where the drainage has been diverted from the southwest into the Snake, to the north and northeast into the Yellowstone River. The studies to be herein reported have shown that the drainage conditions in southwestern Montana are the result of a long series of changes which have been associated with the physiographic evolution of this portion of the Rocky Mountains.

GENERAL GEOLOGIC CONDITIONS.

In the Great Plains there are Paleozoic and Mesozoic formations which rest, in general, in a horizontal position, but are upturned about the centers of volcanic intrusion, and at the east margin of the Rocky Mountains. The later or Cenozoic formations on the Great Plains have been but little disturbed. In the northeast portion of the mountain area, including the Big Belt Mountains, and from there farther to the northwest, there is a core of much deformed pre-Paleozoic rocks which are included in the Belt series. This same series of formations of pre-Paleozoic rocks extends southward through the Phillipsburg region even to the Idaho line northeast of Salmon City. Within the area between these great pre-Paleozoic masses there are other pre-Paleozoic, some Paleozoic, Mesozoic and Cenozoic sedimentary formations, numerous intrusive masses, and some extrusive lavas and tuffs, most complexly associated. All of the pre-Cenozoic formations are more or less disturbed, and even the Tertiary beds are slightly deformed. (See Fig. 51, and Plate XXVIII., *A*.) In the immediate vicinity of Butte and extending northeast nearly to

A. Outwash deposits of the earlier glacial stage resting upon upturned Bozeman beds, near the station of Grace on the Milwaukee Railroad.

B. Morainic deposits of the last glacial stage, in the Deerlodge Valley at the mouth of Racetrack Canyon.

A. Earlier glacial moraines resting upon Bozeman beds, three miles south of Silverbow.

B. Bozeman beds, three miles north of Pipestone Springs southeast of Butte.

A. Boulder-strewn surface of moraines of the earlier stage of Pleistocene glaciation, four miles south of Silverbow.

B. General view of moraines of the earlier stage of Pleistocene glaciation, four miles south of Silverbow.

Helena, there is a large quartz monzonite area known as the Boulder batholith. (See Fig. 51.) About the margins of this batholith there are andesites which once overlay the intrusive mass, also rhyolites and dacites which covered a portion of the batholith after the andesite cover had been in part removed by erosion. In addition there are many porphyry intrusions.

The Tertiary formations rest in the great intermontane troughs. They have been described as the Bozeman Beds.[11] (See Plate XXIX., and Fig. 52.) These deposits may be in part of lacustrine origin, but at all places where I examined them they were found to be great alluvial washes from the neighboring mountain slopes. These deposits have, however, been tilted, and at places notably uplifted. Such movements are interpreted to mean a renewal of mountain growth near the close of Miocene time. The Quaternary formations include glacial moraines of two distinct stages (see Plate XXVIII., *B*, and Plate XXX.), some outwash material from those glaciers, and the modern alluvial deposits in the courses of the larger streams.

Throughout the area there is a pronounced structural unconformity at the base of the Tertiary sediments, which indicates that this re-

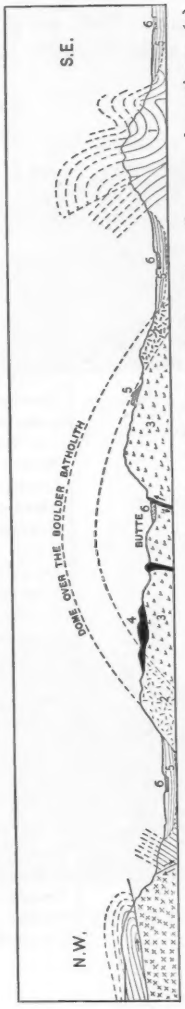


FIG. 51. Diagrammatic section through the Butte district. (1) Paleozoic and Mesozoic sedimentary formations; (2) andesite, flows which formerly covered the batholith; (3) quartz-monzonite of the boulder batholith; (4) rhyolite; (5) Bozeman beds; (6) recent alluvium.

[11] Peale, A. C., U. S. Geol. Survey Geol. Atlas, Three Forks folio (No. 24), 1896.

gion was affected by mountain growth near the close of Cretaceous time. With the growth of the mountain ranges at that time, the physiographic history of the region opened.

GENERAL OUTLINE.

The accompanying table presents an outline of the physiographic events to be set forth in the following pages.

PHYSIOGRAPHIC HISTORY.

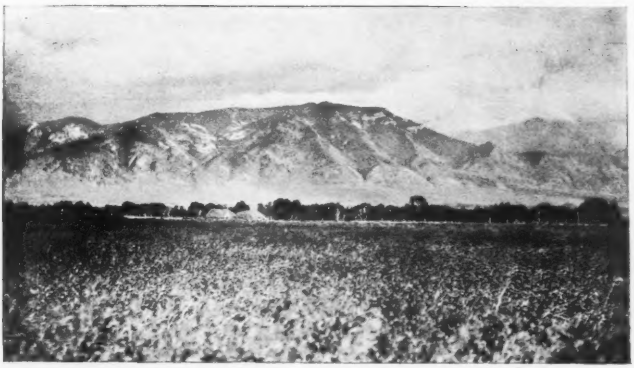
	PHYSIOGRAPHIC EVENTS.
Late Cretaceous	Mountain growth.
Early Tertiary.	Pre-peneplain stage.
Eocene-Oligocene ...	Development of summit peneplain.
	First cycle of erosion.
	Uplift and deformation of peneplain.
Oligocene	Development of great intermontane troughs and a mature topography in the mountains. Deposition of lower Bozeman beds.
	Second cycle of erosion.
Late Oligocene.	Closing of drainage.
Miocene.	Third cycle of erosion in mountains.
Early Pliocene?	Aggradation in lowlands. Deposition of upper Bozeman beds.
	Development of local erosion plains at the "intermediate level."
	Uplift of mountain masses; tilting of Bozeman beds.
	Piracies of the Missouri, Columbia, and Salmon Rivers.
Pliocene	Opening of drainage.
	Fourth cycle of erosion in mountains.
	Dissection of Bozeman beds.
	Superimposed drainage.
	Earlier glaciation.
	Pre-Wisconsin stage.
Pleistocene	Interglacial interval; weathering, erosion, and faulting.
	Later glaciation.
	Wisconsin stage.
	Postglacial interval.
Recent	Stream erosion.
	Piracy of the Yellowstone.

A. Group of rugged mountains west of Apex, which represent a group of monadnocks on the summit peneplain.

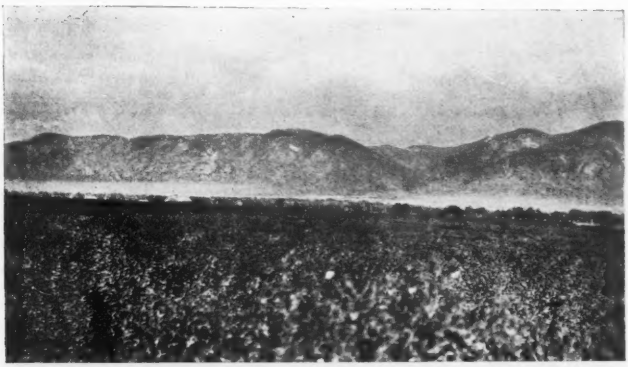
B. Characteristic surface weathering in a quartz-monzonite area of the boulder batholith.

A. Looking upstream into the canyon of Lost Creek, one and one half miles north of Anaconda.

B. Georgetown Lake, the old topography in the midst of the Phillipsburg quadrangle, and a remnant of the summit peneplain in the distance.

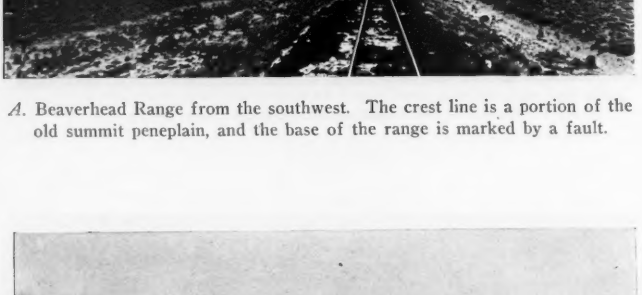


A. West face of the Jefferson Range near Lower Silverstar.



B. West face of the Jefferson Range near Upper Silverstar, showing uniformity of summit level.

A. Beaverhead Range from the southwest. The crest line is a portion of the old summit peneplain, and the base of the range is marked by a fault.



B. Southwest face of Beaverhead Range near Leadore, showing the triangular facets and torrential fans associated with the fault zone.

THE PRE-PENEPLAIN STAGE.

Near the close of the Mesozoic era the then gently rolling surface of western Montana began to warp. The warping continued until there were sharp folds and some faults developed. In time a number of mountain ranges were formed which were comparable in size if not greater than the mountains in that region to-day. As the mountains were elevated erosion was quickened, and the mountain masses were deeply dissected. After the streams had accomplished considerable work, vast flows of andesite were poured out, and later the great Boulder batholith, and doubtless many other similar masses, were forced into the crustal portion of the earth. Following the intrusion of the batholith there was a very prolonged period of erosion during which most of the mountain area was reduced to a lowland of slight relief. That ancient lowland, now recorded in certain mountain crests, was a peneplain. The mountains and hills which rose above that peneplain were monadnocks. (See Plate XXXI., *A.*) That peneplain has since been uplifted, and so warped, broken, and eroded that it is somewhat difficult to recognize. It will be herein referred to as the summit peneplain.

THE SUMMIT PENEPLAIN.

First Cycle of Erosion.

Throughout western Montana and eastern Idaho there are many summit areas which reach an approximately common level between 6,000 and 7,000 feet above the sea. (See Plates XXVI., XXXII., *B;* XXXIII., *B;* and XXXIV., *A.*) At places this summit level is as much as 8,000 feet above sea level. Each crest line of these accordant levels truncates a number of geological formations. These formations, when continued upward, reconstruct in the imagination the mountains of an earlier generation. The plain reconstructed by lifting certain tilted blocks, straightening out some warped surfaces and filling the great intermontane troughs is the old peneplain formed near the close of that cycle of erosion when the earlier generation of mountains were eroded.

This peneplain has been recognized and described in Idaho by

Lindgren and Umpleby, and in western Montana by Calkins. The remnants of the summit peneplain in the Butte district are certain mountain crests. The best preserved remnant near Butte is the ridge running northwest from the Highlands, or Red Mountain. (See Plate XXXVI., *A*.) That crest is clearly visible from the city. The Highlands rise as a conspicuous monadnock above this old erosion surface. Anaconda and Flint Creek Mountains in the Phillipsburg quadrangle are also good examples of monadnocks upon this peneplain. East Ridge is a remnant of the peneplain (see Plate XXVI.), but it has been somewhat dissected, so that the sky line as seen from the west is not as uniform as would be expected for a peneplain remnant. However, an area of granitic rocks always weathers rough in detail. (See Plate XXXI., *B*.) West of Butte, and bordering the Deer Lodge Valley on the east, there is a well-preserved remnant of this peneplain which extends from Silverbow Creek to a point south of Elliston. This crest line cuts across the quartz monzonite and many flows of andesite. Several other remnants of this summit peneplain have been recognized in neighboring quadrangles.

There is no positive evidence as to the direction of drainage during this long period of erosion. Umpleby has suggested that the drainage was to the east. His suggestion comes from the distribution of Eocent sediments east of the Rocky Mountains in Montana and Wyoming, for the erosion of the earlier generation of mountains might have furnished the Eocene sediments in the neighboring plains. The age of this peneplain, based on evidence to be submitted later, is early or middle Eocene.

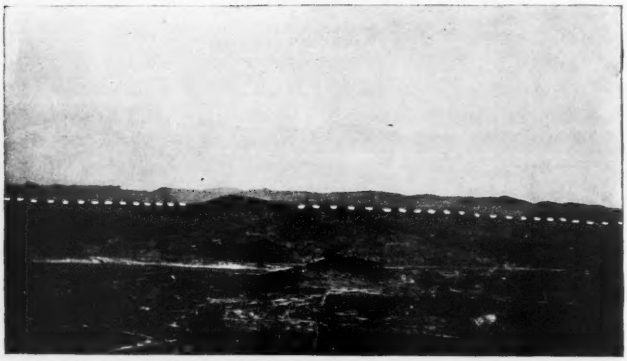
UPLIFT AND DEFORMATION OF THE PENEPLAIN.

Opening of Second Cycle of Erosion.

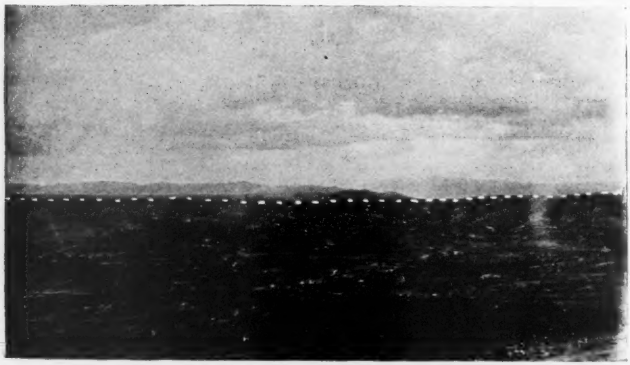
The first cycle of erosion was closed by a very general and widespread uplift of the Rocky Mountain province in western Montana and eastern Idaho. During this uplift it appears that there was some warping of the peneplain surface, and some normal faulting. These movements defined the great intermontane troughs, and determined the location of the main drainage lines.

A. Northeast face of Beaverhead Range, showing uniform summit level and the intermediate or bench level at the dotted line.

B. Southwest face of Beaverhead Range near Leadore. This face is bordered by a fault zone. The low bench at the base of the mountains is due to stream dissection.



A. The sky line is a remnant of the summit peneplain. The intermediate or bench level southwest of Butte is at the dotted line.



B. Intermediate or bench level south of Butte. Continuous with area shown in *A*.

A. West face near the north end of the Oquirrh Range.

B. Entrance to Bingham Canyon on the east side of Oquirrh Range. Bonneville and Provo bench levels shown at left of stream course.

During the period of erosion which followed, certain great passes or gorges were cut through the mountain ranges. Those in the Beaverhead Range may have been cut as the mountain mass rose. The great intermontane troughs, three to five miles wide and 3,000 to 5,000 feet deep, were probably somewhat deepened, and the neighboring mountains were dissected to maturity. The intermontane troughs are to-day second only to the mountain ranges as notable topographic features in this province. Most of them extend in a general north-south direction. The Deer Lodge Valley, the valley of the Jefferson, and the valley of the Missouri southeast of Helena may be taken as good examples. Farther to the northwest the Bitterroot Valley is an excellent example. (See Plate XXVII.) These troughs were even more notable features at the time of their maximum development than they are to-day. The alluvial filling in the Deer Lodge Valley is known to extend at least 1,000 feet below the present stream bed. Even 3000 feet of Tertiary sediments have been described from certain of these troughs.[12]

While the main drainage lines were being deepened the mountain ranges bordering them were being dissected, and remnants of a mature topography have been recognized high among the mountains. During this period, which was the second cycle of erosion, the Continental Divide was far east of the Butte district. (See Plate XXVII. and Fig. 52.) It followed the crest line of the Big Belt Mountains the Bridger Range, and the Gallatin Mountains, to the northwest corner of Yellowstone Park; thence it turned eastward across the present Yellowstone Canyon and followed the crest of the Absaroka Range to a point southeast of the park, where it joined the present Continental Divide.

The drainage lines from southwestern Montana during this period were traced southward into the headwaters of the Snake River. (See Fig. 52.) The broad valleys followed by this drainage cross the Beaverhead Range at low passes, and connect in part with an ancient drainage system of this same period, which has been described by Umpleby.[13] In each of the passes (nos. 23,

[12] Pardee, J. T., "Coal in the Tertiary Lake Beds of Southwestern Montana," U. S. Geol. Survey, Bull. 531, pt. 2, pp. 229–244, 1913.

[13] Umpleby, J. B., U. S. Geol. Survey, Bull. 528, 1913.

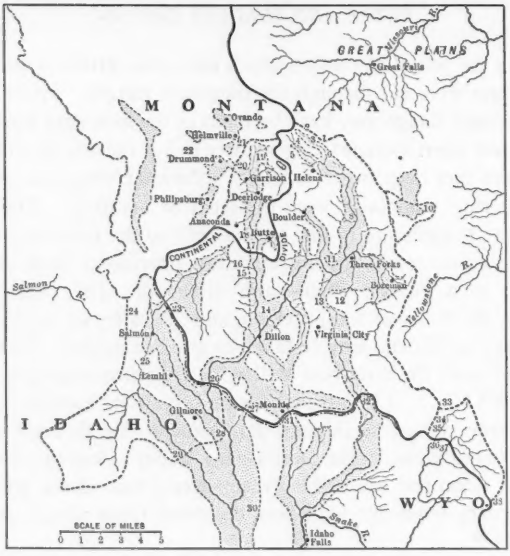


FIG. 52. Map of the distribution of the Bozeman beds in southwestern Montana and northeastern Idaho at the time of their maximum extension. The ancient drainage to the Snake River.

Localities at which drainage conditions demand special explanations: (1) Canyon of the Missouri where piracy occurred; (2) first piracy of Little Prickly Pear Creek; (3) divide in old stream course; (4) second piracy of Little Prickly Pear Creek; (5) divide in old stream course; (6) gorge due to superposition; (7) gorge due to superposition; (8) gorge due to superposition; (9) probable head of Sixteen-mile River before piracy of the Missouri occurred; (10) present head of Sixteen-mile River; (11) gorge due to superposition; (12) gorge probably due to superposition; (13) abandoned stream course; (14) gorge due to superposition; (15) gorge due to superposition; (16) piracy resulting in capture of Big Hole River; (17) divide in old stream course; (18) gorge due to superposition; (19) divide in old stream course; (20) piracy of Hell Gate River; (21) piracy of Nevada Creek; (22) probable piracy of Hell Gate River; (23) Big Hole Pass, a wind gap; (24) canyon of Salmon River, near point where piracy occurred; (25) piracy resulting in capture of the Lemhi and Pahsimeroi Rivers; (26) wind gap northeast of Leadore; (27) small wind gap; (28) divide in old stream course; (29) divide in old stream course; (30) probable former route of drainage to Snake River; (31) pass at Monida, a wind gap; (32) Reynolds Pass, a wind gap; (33) canyon of the Yellowstone where piracy occurred, with capture of Yellowstone Lake and headwaters of Snake River; (34) wind gap; (35) wind gap; (36) wind gap; (37) Two Ocean Pass, a wind gap; (38) junction of former with present Continental Divide.

26, 31, 32, Fig. 52) in the Beaverhead Range there are heavy alluvial deposits. In the pass northeast of Leadore (no. 26, Plate XXVII., and Fig. 52) such deposits are about 1,000 feet thick. They consist of fine silts interstratified with gravels.

In the district immediately surrounding Butte there must have been vigorous erosion. The peneplain was much dissected. Probably much of the weathered material associated with the old peneplain was carried away. Anaconda Hill and the upland surface at and just north of Walkerville are portions of a mature topography developed at this time. To the west, in Brown's Gulch, a valley was cut 400 to 500 feet below the present stream bed. Silverbow Creek, however, did not cut more than a few feet, if any, below its present stream bed, and may not have cut below the bench level just to the south, which is several hundred feet above its present channel.

Before the close of this cycle of erosion alluviation began in the lowlands between the mountain ranges, and the basal portion of the Bozeman Beds were deposited.

CLOSING OF DRAINAGE.

Third Cycle of Erosion.

The further development of the great intermontane troughs, and the great deepening of the tributary valleys in the mountains was interrupted by the closing of drainage in this district. The great outpouring of lava in the Snake River region blocked the drainage in that direction, and that blocking may account in large part for the closing of the drainage in southwestern Montana, but probably there was, associated with the volcanism, some warping in the mountain area, which assisted in closing the drainage. Southwestern Montana became a basin region.

Just north of Butte, and in the western border of the city, there are extensive flows of rhyolite and dacite which appear to have come out at a time when the topography was somewhat rough, perhaps at a stage of mature dissection. The valleys in which the rhyolite occurs were certainly not excavated until the great north-south troughs were developed, and therefore the date of this out-

pouring is placed near the close of the second cycle of erosion, and before the filling of the closed basins. The rhyolites contributed materials to the alluvial fillings, and therefore they antedate, or are closely associated with, the period of filling.

With the closing of the drainage, the great north-south troughs became the sites of aggradation. The upper Bozeman Beds were deposited in these basins; some of these deposits may have been laid down in lakes, but certainly vast quantities of material from the neighboring mountains were carried into the main large valleys, and there deposited as alluvial fans.

The basal portion of the Bozeman deposits have been described as Oligocene in age.[14] They contain coal at several localities. The coal-bearing formation is overlain by deposits of Miocene age, and the uppermost portions of the valley fillings, those washed in by tributary streams, may possibly be of Pliocene age. As the troughs in which these sediments rest were used as drainage lines during the cycle of erosion just preceding the period of filling, and following the uplift and deformation of the summit peneplain, the development of those troughs and of the associated valleys must have been accomplished during late Eocene or early Oligocene time. From this evidence it is clear that the summit peneplain was developed after the close of Cretaceous time, and before the close of Eocene time.

While these great troughs were being aggraded, the streams from the mountain ranges had their base-levels of erosion temporarily determined by the depth of filling in the main stream courses. In many instances the tributary streams reduced portions of their drainage basins to temporary base-levels. This was more commonly true in their lower courses, while farther upstream the topography which they developed was mature. There are many remnants of this intermediate erosion surface. One example is just southwest of Butte (see Plate XXXVI.) at about the same elevation as the site of the Montana State School of Mines but south of Silverbow Creek. Timber Butte rises as a monadnock above that surface (see Plate XXVI.), and farther

[14] Pardee, J. T., "Coal in the Tertiary Lake Beds of Southwestern Montana," U. S. Geol. Survey, Bull. 531, pt. 2, pp. 229–244, 1913.

to the southwest, at the western margin of this intermediate level, is the mountain crest, which is a portion of the summit peneplain. (See Plate XXXVI., *A*.)

In the valley of Bowlder Creek, west of Bowlder, and again north of Bowlder in the valley of Prickly Pear Creek, there are terrace remnants that represent the floors of those valleys during this period of erosion, when the mountain masses were being dissected and the great intermontane troughs filled. Northwest of Deer Lodge there are terrace remnants along the route of Hell Gate River, and also in the valley of Nevada Creek southeast of Helmville. Similar remnants of this intermediate level occur at many other places in the area under study. In certain of the mountain canyons where no such terraces remain, the cross section indicates that there was a halt in the development of the canyon before the modern or inner gorge was cut. The cross section of the valley of Blacktail Creek, southeast of Butte, records in this way two periods in its development. (See Fig. 53.)

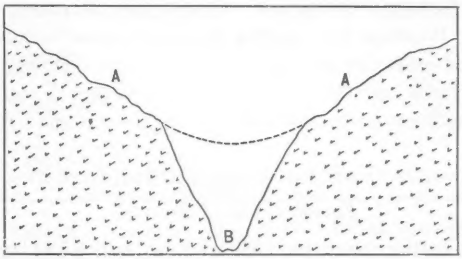


FIG. 53. Diagrammatic cross section of Blacktail Canyon southeast of Butte, showing an upper, outer valley, *AA*, and an inner gorge, *B*.

During this period of erosion in the mountains the rhyolite may have been in part removed from the Butte mining district, and the ore-bearing hills would then have been exposed to further weathering and erosion. The dissection at that time, however, was not below the level of the bench southwest of Butte. The relief about Butte was slight, and the period was somewhat prolonged, so that the underground conditions affecting chemical changes must have remained somewhat constant for a long period of time.

RENEWAL OF MOUNTAIN GROWTH.

The long period of deposition during which the Bozeman Beds were accumulating in the great intermontane troughs was closed by a renewal of mountain growth throughout this portion of the Rocky Mountains. In the pass through the Beaverhead Range northeast of Leadore, Idaho (see no. 26, Plate XXVII., and Fig. 52), the little consolidated sediments of mid-Tertiary time have been uplifted fully 1,000 feet above the floors of the neighboring valleys. At Grace, on the Chicago & Milwaukee Road southeast of Butte, there are Bozeman Beds 1,400 feet above the valley floor to the east. At this locality the Bozeman sediments rest at an angle of about 15 degrees, and are partially covered by glacial outwash gravels. (See Plate XXVIII., *A*.) Mr. J. B. Woodworth has verbally reported to me other examples of uplifted Bozeman Beds in the Tobacco Root Mountains, where basaltic flows have preserved the softer deposits from erosion. In these cases Woodworth indicates that the mid-Tertiary sediments have been uplifted about 2,000 feet. Other examples of uplifted and deformed Bozeman Beds may be discovered when further studies are carried on in this region. This renewal of mountain growth probably came near the close of the Miocene period, and such an uplift must have given renewed vigor to the streams.

PIRACY OF THE MISSOURI AND OPENING OF DRAINAGE.

Fourth Cycle of Erosion.

Late in Tertiary time the Missouri River, which had been working steadily headward toward this region of closed drainage, succeeded in cutting its way through the old Continental Divide northeast of Helena (see no. 1, Plate XXVII., and Figs. 52 and 54) and tapping the area of closed valleys which had formerly been part of the Snake River drainage. The general uplift of the mountain ranges, and especially the uplift of the Beaverhead Range, must have assisted in bringing about this change. Gradually the drainage from southwestern Montana was opened to the northeast, and the Continental Divide was thus forced westward (see Plate XXVII., and Fig. 52) and became located in the

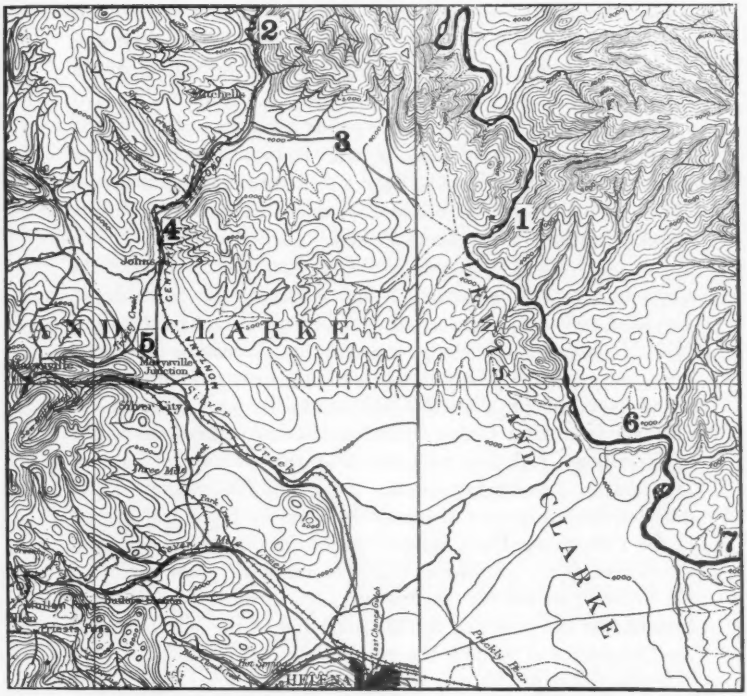


FIG. 54. Topographic map of the region north of Helena where the piracy of the Missouri and of Little Prickly Pear Creek occurred. (Portions of the Helena and Fort Logan quadrangles, U. S. Geological Survey.) Numbers correspond to those on plates II. and XII. (1) Canyon of the Missouri where piracy occurred; (2) first piracy of Little Prickly Pear Creek; (3) divide in old stream course; (4) second piracy of Little Prickly Pear Creek; (5) divide in old stream course; (6) gorge due to superposition; (7) gorge due to superposition.

midst of the boulder batholith southward to Red Mountain, and thence westward to the Anaconda Range, southwest to the Beaverhead Range, and eastward to Yellowstone Park. During this same period of time the headwaters of the Salmon River in Idaho

worked headward, cutting a magnificent gorge, and in time captured the drainage from the broad, open, waste-filled valleys just southwest of the Beaverhead Range. Thus the waters of the Lemhi and Pahsimeroi Valleys were turned northward.[15]

Numerous minor cases of piracy took place about the margins of the area which the Missouri River was capturing. Northwest from Helena, Little Prickly Pear Creek committed piracy near Mitchells, and again near Silver City, where the waters of Canyon Creek were diverted to the northward. (See Plate XXVII., and Fig. 52.) Nevada Creek and Hell Gate River, headwaters of the Columbia, secured portions of the old Snake River drainage. Nevada Creek worked eastward from Helmville (see no. 21, Plate XXVII., and Fig. 52) and captured the drainage of a broad open valley, and Hell Gate River, working headward from Drummond (see no. 20, Plate XXVII., and Fig. 52), diverted the drainage from Deer Lodge Valley, and in time secured the waters of Silverbow Creek, and with that the entire drainage of the area immediately surrounding Butte. Later the Yellowstone River diverted the headwaters of the Snake River in the central portion of the Yellowstone Park, and shifted the Continental Divide from the eastern to the southwest margin of the Park. The piracy of the Yellowstone has been determined as postglacial,[16] but it is not evident that the piracy of the Missouri and of the headwaters of the Columbia and Salmon Rivers were quite as late as that.

These drainage changes have been indeed remarkable. The Continental Divide was shifted at least 150 miles to the westward, and about 8,000 square miles of territory were added to the drainage of the Missouri River basin. About 300 miles of the old Continental Divide were abandoned. (See Plate XXVII., and Fig. 52.)

With the reversal of drainage from southwestern Montana the streams were in time rejuvenated, and the great alluvial fillings, of Oligocene, Miocene, and possibly in part Pliocene age, in each

[15] Umpleby, J. B., "Geology and Ore Deposits of Lemhi County, Idaho," U. S. Geol. Survey, Bull. 528, p. 30, 1913.

[16] Goode, J. P., "The Piracy of the Yellowstone," *Jour. Geology*, vol. 7, no. 3, p. 261, 1899.

of the large valleys, were dissected. The fourth cycle of erosion was thus begun. As dissection advanced, many streams cut their channels into the alluvial fillings at one side or the other of the old buried channel. They were superimposed streams. Such streams soon uncovered bed-rock in portions of their courses, and at those places, as they lowered their channels, narrow rock gorges were developed. (See nos. 8, 11, 14, 15, Plate XXVII., and Fig. 52.) The anomalous valleys of many of the present streams, with their short but sharp narrow gorges and their broad open courses, may, in most instances, be accounted for by superposition of the streams. The dissection of the alluvial filling has continued to the present day, and at many places broad valleys have been worked out. It is important to note, however, that the present valley bottoms, the present base to which the streams can cut, is many hundreds of feet above the floors of the great intermontane troughs.

In the immediate vicinity of Butte the streams carried away all alluvial material and much of the weathered surface rock.

GLACIATION.

During the last period of erosion there have been at least two stages of glaciation. The evidence of the earlier stage of ice work has been largely removed, but the evidence of the last, or Wisconsin stage, is abundant.

Pre-Wisconsin Stage.—The most satisfactory, positive, and significant evidence of this earlier stage of ice work is southwest of Butte, in the broad open valley directly south from Silverbow. (See Plate XXX.) The evidence here consists of a very massive deposit of till which retains a faint morainic topography. Boulders which range up to 25 feet in diameter are abundant. The hills are arranged as an irregular ridge, which, when followed southward, is found to be related to the amphitheatral area at the head of Basin Creek, as a great lateral moraine. Traced northward these morainic hills come to the Silverbow Creek a little east of Silverbow station. The ice which formed that moraine must have covered the entire area from the Highlands, or Red Mountain, northward to Butte, and that ice may have covered the area where the city is now located.

No morainic deposits were seen on the bench southwest of Butte, or on the Flat southeast of the city. The earlier ice must have rested against the west face of East Ridge, but no morainic deposits were found on or at the base of that ridge. The absence of positive evidence of ice action in the lowland area south and southeast of Butte must be due in part to stream erosion since that ice left, but it may be due in part to burial beneath the alluvium of the Flat. The ice which rose over the mountain ridge to the west of this area surely occupied the lower country east of that ridge.

Along the route of the Chicago, Milwaukee & St. Paul Railroad, southeast from Butte and near the little station known as Grace, there is a coarse alluvial deposit in which there are striated stones. (See Plate XXVIII., *A*.) This wash material is high above the main valley of Fish Creek, and beyond the point reached by the ice of the later glacial stage. This material and its topographic position have led to the interpretation that ice of a pre-Wisconsin stage in Fish Creek Canyon advanced northeastward from Red Mountain, and spread over the country now bordering that canyon. The waters issuing from that earlier ice distributed the material now exposed in the railroad cut and traceable northeastward for nearly a mile into the valley of Little Pipestone Creek. The location of this material suggests that the present inner gorge of Fish Creek Canyon did not exist at the time of the earlier glacial stage.

East of Butte, in the region of upper Whitetail Park and thence along the route of Whitetail Creek, there is positive evidence of ancient glaciation. There is no proof that ice occupied upper Whitetail Park during the later glacial stage, or followed the route of Whitetail Canyon, but beyond the great andesite hills and high on the east-facing slope of the valley of Little Whitetail Creek there are huge granite boulders, ranging up to twenty feet in diameter, which must have been brought by ice coming from the westward. These boulders reach to at least a thousand feet above the present stream channel. They are not in the modern valley. Such evidence indicates that there has been a long period of erosion since the ice which left these boulders occupied the

valley of Whitetail Creek. South of Butte, and near the headwaters of the east fork of Basin Creek, there is an ancient cirque which was not occupied by ice during the later stage. In the east wall of Elk Park there are several other amphitheatral basins which were not occupied by ice during the last glacial stage, but certainly were during some earlier glacial stage. Elk Park was largely developed by ice erosion during this earlier stage of glaciation. About eight miles north of Butte there are distinct glacial deposits still retaining some striated stones, and this material was derived from cirques a little farther to the northeast near the Continental Divide. One of the city reservoirs is located in the larger of these cirques. But again these cirques were not occupied by ice during the later or Wisconsin glacial stage. Other evidence of an earlier glacial stage was found in the mountains southeast from Helmville, and again south of Anaconda.

Most of the evidence of pre-Wisconsin glaciation near Butte may, with a high degree of probability, be correlated with the earlier stages of Pleistocene glaciation reported in the Uinta and Wasatch Mountains,[17] in the Bighorn Range,[18] Sawatch Range,[19] Cascade Mountains,[20] and many other of the western mountains. In the San Juan Mountains, however, three stages of Pleistocene glaciation have been recognized, and the probable correlation of some of the earlier moraines near Butte would be with the intermediate or Dallas stage,[21] while other of these earlier moraines, especially those just south of Silverbow and those near Grace, may belong to the still earlier or Cerro stage.[22]

[17] Atwood, W. W., "Glaciation of the Uinta and Wasatch Mountains," U. S. Geol. Survey, Prof. Paper 61, 1909.

[18] Darton, N. H., and Salisbury, R. D., U. S. Geol. Survey Geol. Atlas, Cloud Peak–Fort McKinney folio (no. 142), 1906.

[19] Capps, S. R., and Leffingwell, E. D. K., "Pleistocene Geology of the Sawatch Range, near Leadville, Colorado," *Jour. Geology*, vol. 12, no. 8, pp. 658–706, 1904.

[20] Willis, Bailey, and Smith, G. O., U. S. Geol. Survey Geol. Atlas, Tacoma folio (No. 54), 1899.

[21] Atwood, W. W., and Mather, K. F., "The Evidence of Three Distinct Glacial Epochs in the Pleistocene History of the San Juan Mountains, Colorado," *Jour. Geology*, vol. 20, no. 5, 1912.

[22] Atwood, W. W., "Eocene Glacial Deposits in Southwestern Colorado," U. S. Geol. Survey, Prof. Paper 95–B, 1915.

Later or Wisconsin Stage.—Evidence of the later glacial stage is very abundant. There are fresh moraines and recently cleaned out cirques on the north slope of Red Mountain, and in each of the higher basins of the Anaconda and Flint Creek Ranges. Numerous other examples were seen in the Tobacco Root Range, and in the mountains just west of Apex and northwest from Dillon. The moraines of this later glacial stage, on the west slope of Deer Lodge Valley, are remarkable formations. I have never seen such heavy terminal moraine deposits from a small alpine glacier as those which exist just beyond the mouth of Racetrack Canyon. (See Plate XXVIII., *B.*) Those associated with the Rock Creek Canyon, northwest from Deer Lodge, are also remarkable deposits. These younger moraines retain their hummocky topography, and they are strewn with immense boulders, they are arranged in lobate forms beyond the mouth of the canyon, and their symmetry is such that it is but a slight mental effort to replace the ice which formed them. From the terminal moraines huge lateral moraines extend upstream along the canyon walls. Most of these later glaciers reached just beyond the mountain canyons, and deployed in the broad, open valleys between the ranges. The cirques in which the later glaciers of the Flint Creek Range formed were not visited, but from a distance they appeared to be well cleaned out, and bordered by precipitous walls. They appear to retain that same fresh record of glaciation which characterizes all higher mountain areas in the western part of the continent. This glacial stage may safely be correlated with the Wisconsin stage of continental glaciation.

During the glacial and inter-glacial stages of the Pleistocene period the great canyons of the mountain ranges have been developed.

THE FLAT AT BUTTE.

In the study of the physiographic development of the Butte district the history of the Flat has been a special puzzle. This lowland area is not a normal river flood plain. It is not a basin gouged out by ice among the mountains. The alluvium beneath its surface is known to vary up to 600 feet in thickness. The greatest known depth of alluvium is at the shaft of the Pittsmont

mine, about two miles east of Anaconda Hill. East, west, north and south from that locality the depth of alluvial filling is known to decrease in thickness. The rock surface beneath the Flat is at places lower than the rock surface in the bed of Silverbow Creek near Rocker, five miles west of the Flat. These conditions indicate that the Flat is an alluvial filling in a depressed area. The bold face of East Ridge, at the east margin of the Flat, and the triangular facets on certain of the rock spurs extending west from the ridge, are physiographic evidence that there has recently been faulting at the west base of East Ridge. The underground workings at certain of the mines have demonstrated this faulting, and the surface operations at the Bullwhacker mine have uncovered a portion of the fault zone. Figure 55, taken from Sales's paper,[23] shows the underground conditions east of Anaconda Hill to and beyond the fault zone. The date of the faulting is placed in the physiographic history some time after the opening of the fourth cycle of erosion, and probably after the earlier stage of glaciation. The topography where the Flat now is was probably somewhat like that shown in Fig. 56, before the faulting took place. After the faulting, alluviation began, and little by little the erosion topography in the downfaulted block was buried. As the burial continued the Flat became wider, and in time drainage was reëstablished to the westward by Silverbow Creek. The surface alluvium in the Flat consists of arkose material derived from the neighboring granitic hills.

SECONDARY ENRICHMENT OF THE ORES.[24]

DURING THE FIRST CYCLE OF EROSION.

The origin of the primary ores in the Butte district is generally believed to have been associated with the cooling of the great quartz-monzonite batholith. When the ores were formed there was probably a cover of andesite, perhaps not less than 3,000 feet

[23] Sales, R. H., "Ore Deposits at Butte, Montana," *Am. Inst. Min. Eng. Trans.*, vol. 46, 1913.

[24] The work on which this paper was based was done in association with the Secondary Enrichment Investigation, but the responsibility for the application of physiography, as herein presented, rests entirely with the writer.

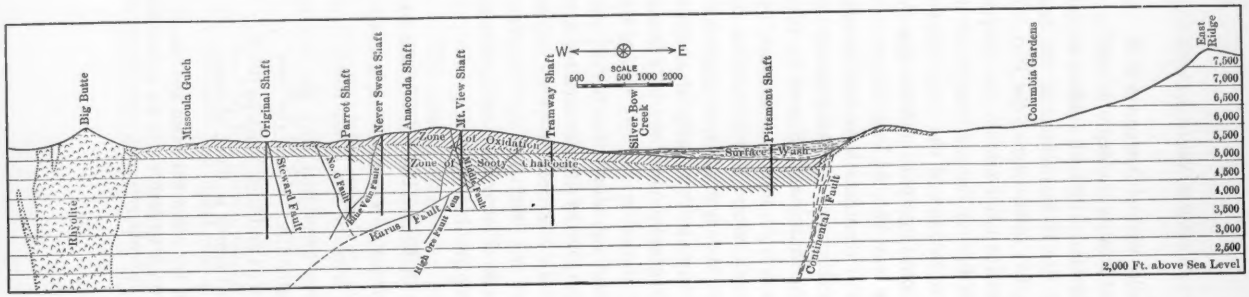


FIG. 55. Vertical section taken along the general course of the Anaconda vein, showing relation between the oxidized and sooty chalcocite zones and the continental fault. The section is idealized in region east of Pittsmont shaft (Sales).

thick, over the batholith.[25] During the first cycle of erosion in the Butte district, when the summit peneplain was developed, much of the andesite was removed, and the quartz-monzonite was exposed at the surface. That period or cycle of erosion must have been very long, and if mineral veins reached near to the surface at that time, the descending meteoric waters may have accomplished a certain amount of secondary enrichment of the ore bodies. There is, however, no field evidence of secondary enrichment of that date. It may have existed, but the summit peneplain about Butte has been so dissected during the later cycles of erosion that it is very probable, if such secondary ores did exist, that they have since been either carried away by surface erosion, or been carried lower by ground waters in a later period of enrichment. The fact that many of the ore bodies in this district do not reach the present surface suggests that there was little opportunity for secondary enrichment during the first cycle of erosion. It is perfectly apparent that secondary enrichment cannot take place when the ores do not reach upward into the zone of oxidation.

DURING THE SECOND CYCLE OF EROSION.

The second great cycle of erosion in the Butte district was inaugurated by a general uplift of the region. The peneplain was uplifted, warped, and faulted. The great intermontane troughs were formed. The rejuvenated streams began at once to entrench their courses, and in time they dissected the mountain ranges to maturity. The higher lands in the Butte area reached the stage of sub-maturity. The rhyolite flows north and northwest of the city flowed out upon this topography, and have preserved at their base a portion of that old topography. The present distribution of the rhyolite suggests that most, if not all, of the mining district at Butte was formerly covered by such flows. In the immediate vicinity of Butte the top of Anaconda Hill and the district near and north of Walkerville very nearly represent the topography of that stage. They have been modified but little since then.

While the dissection of the region was in progress, the ore

[25] This statement has been carefully qualified, for the suggestion has been made recently that the Boulder batholith did not have a cover.

bodies which reached into the zone of oxidation must have been affected by descending ground waters. Much surface material was carried away, and, if the ore bodies were not in the zone of oxidation at the opening, it is certain that they were before the close of the period. In the zone of oxidation the metallic minerals would have been dissolved, to be in turn precipitated in the lower zone of enrichment. The lower limit of the zone of oxidation is generally believed to be fixed by the ground-water table, which here must have had an undulating surface, rising in the hills and descending toward, if not to, the permanent streams of the region. In detail the water table must have been quite irregular, being higher in the compact and lower in the looser or more fractured portions of the hills. The main stream draining the region immediately south of Butte had its base-level of erosion determined by the depth of cutting of the large valley to the west. That stream may have cut to the level of the bench southwest of Butte, but it does not appear that it cut lower than that surface at that time. The maximum depth of the ground-water table was not below the bench level, unless we assume a period of extreme aridity. There is, however, no basis for assuming such aridity at this time. Anaconda Hill rose somewhat above that level, and the great ore bodies in that hill were favorably located for oxidation and enrichment. This is believed to have been the first important period of secondary enrichment.

DURING THE THIRD PERIOD OF EROSION OR THE CYCLE OF CLOSED DRAINAGE.

During the third cycle of erosion the great north-south troughs were being filled. The base-level of erosion for the tributary streams, determined by the filling in of the main large valleys, was elevated several hundred feet. The streams about Butte widened their valleys and developed a local base-level surface, which is now referred to as the bench-level. At that time an old erosion surface at the general elevation of the bench southwest of Butte extended northward to Anaconda Hill, eastward and northeastward to the mountain ridge bordering the Flat. (See Plate XXXVI.) The spurs near the Columbia Gardens east of

Butte are remnants of that old surface. They have become distinct topographic features by subsequent stream erosion. The streams near Butte were then the headwater streams of a larger river, which flowed southward from Silverbow toward the site of Dillon. (See Fig. 52.) The elevation of the base to which the streams were cutting would in general mean the rise of the water table near the larger valleys, and in so far as that table rose through an ore body the zone of oxidation was decreased in depth, and the horizon at which secondary enrichment might take place was brought nearer to the surface. The nearest one of the large filled troughs to Butte is Brown's Gulch, which is about five miles west of Anaconda Hill. The change in the water table at Butte due to that filling was probably very little, if any. In the last stages of the development of the local peneplain there was a long and favorable time for complete oxidation of the ores above the water table, and the appropriate enrichment of the ores at and below that table. During this time the upper slopes of Anaconda Hill came to have about their present forms. They were being eroded by streams cutting to the bench-level. This was the second and last important period of secondary enrichment. As the solutions descended, they would have become less and less rich in copper, and the amount of secondary enrichment must have become less and less with increased depth. At that time the movement along the continental fault zone (see Fig. 56) had not taken place, and therefore the bed-rock now deeply buried beneath the alluvium of the Flat was at the surface. The mining work has shown clearly that the zone of oxidation continues eastward from Anaconda Hill below the alluvium of the Flat. This zone is strongly marked, and very easily traced underground. In the hill it is about 400 feet thick, but under the Flat it is reported as somewhat less in thickness.

The zone of "sooty" chalcocite, as described and defined by Sales, records throughout its extent a secondary enrichment of the copper ores, and also extends from Anaconda Hill eastward below the buried zone of oxidation underneath the Flat. From the available data it appears that the amount of secondary chalcocite beneath the Flat is somewhat less than that in Anaconda

Hill. Fig. 55, prepared by Mr. Sales, indicates that the base of the "sooty" chalcocite zone is quite irregular, but in detail it is so irregular that it could not be adequately shown in a single cross-section drawing. The maximum depth to which secondary enrichment has proceeded is probably much more irregular than the base of the "sooty" chalcocite zone as recognized in the mines. The form of the secondary ore body suggests that the

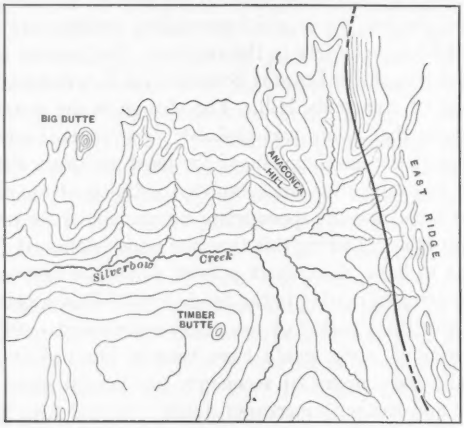


FIG. 56. Idealized topography in the area of the "Flat" before the movement along the continental fault took place.

descending waters have been more abundant along certain lines, perhaps where the rocks were more crushed and fractured, and that the processes of enrichment have therefore descended deeper at such places. Sales states that secondary changes have not been so complete in the lower portion of the zone of "sooty" chalcocite, and that the lower margin of the zone is a blended margin, with a gradual transition to the primary ores below. In Anaconda Hill the secondary enrichment is known to extend at least 1,100 feet below the base of the zone of oxidation, and under the Flat it is reported that the secondary ores descend 300 feet below the base of the zone of oxidation. In actual elevation above sea-

level the base of the enrichment zone under the hill stands at about 4,600 feet, and under the Flat at about 4,500 feet.

These underground conditions, now fully demonstrated by the mine workings, are of special significance in the interpretation of physiographic history. The zones of oxidation and secondary enrichment buried beneath the Flat have evidently been depressed and buried since the notable chemical changes in those two zones took place. The underground conditions, therefore, place the date of the faulting and the development of the great Flat later than the extensive oxidation and enrichment of the ores. If the downfaulted block were lifted back into the place it formerly occupied, an erosion topography (Fig. 56) would exist where the "Flat" now is, and it would be apparent that the erosion topography was due to the dissection of the intermediate or bench-level represented south of Butte and in the spurs at the base of East Ridge. Therefore, the faulting took place after the third cycle of erosion. Most of the secondary enrichment had probably been accomplished by the close of that same cycle.

DURING THE FOURTH CYCLE OF EROSION.

The reëxcavation of the great north-south valleys and the deepening of the tributary valleys marked the beginning of the next cycle of erosion, which, though locally interrupted by glaciation, has continued to the present day. During this last cycle there has been a deepening of the drainage line which has very slowly lowered the water table, and therefore slowly deepened the zone of oxidation and increased the depth to which the secondary enrichment might take place. During each glacial stage the abundance of rainfall must have temporarily raised the water table, and the aridity of the interglacial stages and of postglacial time must have lowered that table.

CONCLUSION.

From these studies it would appear that the Butte district has passed through at least four stages of erosion. The first of these was a more nearly completed cycle than either of the others. During the first erosion cycle secondary enrichment may have been in progress, but there is no evidence of that period of enrichment

left. During the second and third cycles physiographic conditions were favorable for the enrichment of the ores, and the enrichment processes have undoubtedly continued during the fourth cycle.

If the Butte ores were ever affected by secondary changes to a greater depth than they are at present being affected, it was during the second cycle of erosion. That was the period when the great north-south troughs were deeper than they are to-day. The reported depth of at least 800 feet of filling near the east side of Brown's Gulch suggests that the bottom of that trough may be still deeper, and during the second cycle of erosion may have caused the lowering of the ground-water table. The middle of that gulch is, however, five miles distant from the ores under consideration, and in a mountainous district of moderate to heavy rainfall could not have had much effect on the position of the water table in those ore bodies. The bed-rock surface in the Silverbow Valley near Rocker is reported as certainly not more than 20 feet below the stream bed. The rock outcrops bordering the stream channel support that statement, and it would therefore appear that the stream has never cut but little deeper than to-day. There is no proof available that the area about Butte and to the south was occupied by Tertiary fillings such as occupy the large north-south troughs. Furthermore, the zone of oxidation beneath the modern alluvium in the "Flat" indicates conclusively that the now depressed land was above the level of the "Flat" and probably up to the bench-level at the time when the oxidation and enrichment took place. The base of the buried zone of oxidation beneath the central portion of the "Flat" where the Pittsmont mine is located is between 500 and 700 feet below the surface. That horizon must have been at least as high as the present surface of the "Flat" at the time, before the faulting, when the oxidation and enrichment of the ores took place. It was probably higher than that by three or four hundred feet, which would make the amount of depression at this place about 1,000 or 1,100 feet. This depression was due to the movement along the continental fault, but does not necessarily give the maximum amount of movement along that fault.

There is, therefore, no positive physiographic evidence in the Butte district that there could have been an enrichment of the ores to greater depth than such enrichment may go on to-day. The secondary enrichment, which was well advanced by the close of the third cycle of erosion, must have been deepened somewhat, at least in Anaconda Hill, as the fourth cycle advanced. As the streams deepened their courses, ground waters were drawn off from the hills, and the general level of the ground-water table was thus lowered. Oxidation extended to greater depth in the hills, and continued down the valley slopes to the horizon at which continuous seepage into the permanent streams took place. The bed of the streams may have actually been in or upon enriched ores. The erosion of this cycle succeeded in somewhat dissecting the local base-level plain near Butte before the stream work was interrupted by the earlier stage of glaciation. The absence of glacial deposits about the margin of the "Flat" or near the city of Butte, especially at the east margin of the "Flat," is indeed remarkable, if that ice advanced into the region after the "Flat" had been developed. Furthermore, the base of East Ridge and the ends of spurs near the Columbia Gardens should retain some indications of ice work, if the faulting had taken place prior to the earlier ice advance. Since the evidence is satisfactory that ice advanced from the south northward as far as the city of Butte, it is much more reasonable to infer that the faulting at the east margin of the "Flat" has occurred since the earlier glacial stage. When the faulting took place drainage was ponded where the "Flat" now is, and the wash from the neighboring mountains accumulated in the depressed area, until drainage was reëstablished to the westward by way of the Silverbow Creek. As the filling went on, the ground-water table must have been near the surface of the alluvium. The area of the "Flat" became larger and larger as the filling grew deeper, and the abruptness of the neighboring hills is in part accounted for by the development of the flat surface in this large waste-filled area. The later stage of glaciation did not affect the immediate area near Butte.

As the water table beneath the "Flat" rose, after faulting had taken place, the oxidation in the upper zone ceased, and there-

fore the enrichment of the ores below that zone ceased, unless there were waters coming in from other directions. Thus the lesser thickness of the zone of oxidation and of the zone of enriched ores beneath the "Flat," in comparison to those zones in Anaconda Hill, may be in part accounted for. In Anaconda Hill the enrichment has continued on to the present time, while beneath the "Flat" the secondary alterations of the ores ceased soon after the faulting took place.

The physiographic evidence of faulting at the east margin of the "Flat" is so clear that the determination of movement along this line could have been made without the assistance of underground work. The date of this faulting is best determined by physiographic methods, and it may not be too much to claim that had detailed physiographic studies been carried on in the Butte region before development work under the "Flat" had begun, the history of the "Flat" might have been worked out, and the determination made that beneath the alluvium there was a downfaulted block which had formerly stood in a favorable position for the secondary enrichment of ores.

Regarding the enrichment of the Butte ores Lindgren states:[26]

"The problem of enrichment at Butte is complicated and it has been suggested that after some of the enrichment had taken place there occurred a repeated invasion of ascending waters, perhaps depositing enargite. In explanation of the deep chalcocite zone Emmons and Weed state that the block in which the veins are contained has been faulted down probably several thousand feet, and that thus the water level might formerly have stood lower than at the present time. This explanation is not satisfactory, for it is not probable that the water level in this region has ever been at a considerable depth below the surface, and in the adjacent and higher block on the east the water level still remains high. It is conceded that the present barren zone was created by leaching of the former upper part of the chalcocite zone, and that during this process the copper was sharply concentrated in the upper part of the present enriched zone. Therefore, the latter, like many other bodies of secondary chalcocite, must be of considerable geological age and long antedate the faulting. When it was accumulated that water level was assuredly much higher than at present."

[26] Lindgren, Waldemar, "Mineral Deposits," pp. 820–21, 1913.

It is evident that the enrichment of the Butte ores presents many difficult problems. From the physiographic studies it would appear that there have been two periods when the conditions must have been favorable for the secondary enrichment process for considerable periods of time. The physiographic studies support the conclusion which Lindgren reached that the great secondary enrichment of the ores long antedated the faulting east of Butte, and that when the enrichment took place the water level was much higher than it is at present.

The application of physiography to the study of secondary ores must first be established by the examination of mining districts where there is a sufficient amount of underground data available to assist in working out the principles involved in this application. In the Butte district the nature and extent of the larger ore bodies have probably been established, and therefore the region is an excellent one in which to work out the relationship of the physiographic history to the secondary changes in the ores, but it could hardly be expected that this study would reveal more than was known regarding the distribution of the Butte ores. The Bingham Canyon ore body is not yet defined. The results which have been obtained assure confidence in the importance of similar studies in other mining regions. The complete geological history of secondary ores cannot be worked out without an appreciation of the cycles of erosion which have affected the region where those ores exist. It is of importance to determine the interruptions which have come in the midst of the erosion history. Possibly stream piracy has occurred, or through faulting or other earth movements the entire system of drainage may have changed, or the base to which the streams were cutting may have been changed. In other regions the outpouring of lava has affected the drainage. Perhaps lava flows have mantled an area where secondary enrichment had begun, and the process of enrichment was interrupted until that lava flow was removed. In some districts there may have been two or three periods of enrichment; there may have been periods when enrichment went much deeper than it does to-day. Undiscovered bodies of secondary ores may be deeply buried beneath recently deposited materials, or beneath lava flows.

Possibly, through physiographic studies, the location of ore bodies may be inferred in certain hills or certain lowlands which adjoin areas where ore bodies outcrop at the surface. Possibly certain abandoned mining camps could be profitably re-examined, or the development of new mining camps directed, in part, through the application of the principles which should be developed by the application of physiographic methods in the study of ore deposits.

The studies which have been recently carried on indicate that the secondary enrichment in the western mountains is of late geologic date. Probably most of the secondary ores in the western portion of North America have been produced during Tertiary and Quaternary time.

PART II. PHYSIOGRAPHIC CONDITIONS AT BINGHAM CANYON, UTAH, WHEN THE COPPER ORES IN THAT DISTRICT WERE ENRICHED.

INTRODUCTION.

Following the study of the region about Butte, Montana, there remained, during the month of August, 1914, about ten days which could be devoted to the study of another mining camp. Mr. E. H. Perry accompanied me to the Bingham Canyon region, and was associated with me in the studies to be herein described. I am especially indebted to Mr. Perry for detailed information pertaining to the underground conditions, and to the nature and distribution of the secondary ores in this district.

Most of the time available was spent near Bingham Canyon, but the summit area was thoroughly explored and an excursion was made completely around the range. After returning from this excursion an ascent to the summit was again made, so that the general relationship of the great uncovered body of secondary ores to the present topography could be appreciated.

Bingham Canyon is on the east side of the Oquirrh Mountains, the first range in the great desert west of the Wasatch Mountains. (See Plate XXXVII., *B*.) This desert range is about

thirty miles in length, and from five to ten miles in width. The north end is but twenty miles west of Salt Lake City, and less than two miles south of the present south margin of Great Salt Lake. The highest summits in this range reach to 10,250 feet above sea level, but a large portion of the summit area stands at about 8,000 feet above tide. These mountains are, however, strikingly conspicuous features, for they rise 4,000 to 6,000 feet above the extensive flats of Lake Bonneville. The elevation of the ancient lake floor is about 4,500 feet. The Bonneville shore line, which is recorded by a lake cliff and usually by a broad, wave-cut and wave-built terrace, is well preserved at many places about the base of the range. The Provo shore line is even better shown at certain localities about the margin of the mountains.

There are a few permanent streams in this range, but they are commonly very small. The higher slopes are clothed with coarse grasses, and there are some trees on slopes which face to the north and northeast, where the snows remain longest or rain waters are not so quickly evaporated. The annual rainfall in the range is probably between 10 and 20 inches, but on the lowlands bordering the range the rainfall is less than 10 inches per year. Climatic conditions have, however, varied greatly in this province during late geologic time. High-water stages existed in the Bonneville basin during each of the stages when glaciers formed in the Wasatch Mountains, and during the interglacial intervals when the ice melted away from the high mountains, there were periods of desiccation in the Great Basin.[27] When the snowfall was heavy in the Wasatch and all of the Rocky Mountains the Basin Ranges must have enjoyed an abundant rainfall. The early Tertiary glaciation in the San Juan Mountains of Colorado[28] suggests that there may have been glaciers in the higher mountains of Utah at that same time. The variations in rainfall directly affected the amount of water in the ground, and the changing of the lake level in the great Bonneville

[27] Atwood, W. W., "Glaciation of the Uinta and Wasatch Mountains," U. S. Geol. Survey, Prof. Paper 61, 1909.

[28] Atwood, W. W., "Eocene Glacial Deposits in Southwestern Colorado," U. S. Geol. Survey, Prof. Paper 95-B, 1915.

Basin changed the level to which the ground waters were sinking. As the ground-water table was raised or lowered, the depth of the zone of oxidation was varied, and therefore the upper horizon at which the secondary enrichment of ores commonly takes place was shifted. The complete solution of the physiographic history of the region may therefore make some important contributions to the history of the secondary enrichment of the ores in the district. This report is based on but a few days of field work, and should be accepted as an outline of a problem the solution of which may involve the study of a large portion of the Great Basin, and should certainly include a careful study of the physiographic evolution at several of the mining camps in the Great Basin.

GENERAL GEOLOGY.[29]

The Oquirrh Range consists of a great series of Paleozoic sediments which are chiefly limestones and quartzites. These formations have been folded and faulted and later affected, especially in the region about Bingham Canyon, by the intrusion of great masses of monzonite-porphyry. The intruded rocks are evidently post-Carboniferous, but how much later it is impossible to say. Much later than Paleozoic times, later even than the physiographic development of the present range, and even after the dissection of this range, there were vast quantities of andesitic lavas poured out over the eastern slope in the southern half of the range. In the south half of the Oquirrh Range there are two great anticlines and an included syncline, with axes which run in a northwestward direction, or diagonal to the general trend of the range. The axes of these anticlines have a general pitch to the northwest. North of the Bingham Canyon district there are great thicknesses of quartzites dipping to the northwest, and beyond these there are heavy beds of limestone. Faulting is much more common in this northern portion of the range than in the southern half. The northwest face is a fault scarp, and the north-

[29] The chief source of information on the general geology and ore deposits of this district is the excellent paper by J. M. Boutwell.

Boutwell, J. M., "Economic Geology of the Bingham Mining District, Utah," U. S. Geol. Survey, Prof. Paper 38, 1905.

ern end owes its abrupt form to faulting. The contrast in the physiographic forms in the northern and southern parts of the Oquirrh Range is distinct, and will be referred to later. The division line is a general east-west zone of displacement extending through Butterfield Canyon on the east slope into the Tooele Canyon on the west slope. The lowest pass on the range connects the heads of these two canyons. The significant features in the geological conditions of this range to the physiographer are (1) that the great series of sedimentary formations has been upturned, folded, faulted and affected by intrusion; (2) that neither the folding nor the faulting corresponds in any simple manner to the present general form of the range; (3) that the summit region is an erosion topography formed on the edges of strata and over masses of monzonites.

PHYSIOGRAPHY.

The east slope of the Oquirrh Range is bold in the northern portion, but at the south the low andesitic hills make the approach from the east very gentle. The mountain spurs at the north on the east side do not end abruptly but grade into the alluvial deposits of Lake Bonneville. The eastern face of the range is therefore interpreted as an erosion topography. Great step-like benches of the ancient lake are well shown along this east face of the range. The west slope of the Oquirrh Mountains must also be described in two parts. The northern half, that north of Tooele, has a remarkable escarpment which truncates the intervalley spurs in such form as to indicate that there has been faulting at this margin of the range. The line of this fault enters the range east of Tooele. Southwest of Bingham in the high mountain area a fault zone was located which is probably the continuation of the zone of movement which now defines the west face of the mountains in their northern half. (See Plate XXXVII., *A*.) The southern half of the west slope appears somewhat bold, as does the northeastern slope of the range, but the mountain spurs project into the lowland area, and they project to very different distances. There is no such sharp limitation as in the northern half of the west front. The topography of the southern half of the west face is interpreted as an erosion topography.

The summit of this range of mountains is somewhat uneven. In the northern half there is a general correspondence in elevation at about 8,000 feet. In the central portion the summits reach to something over 10,000 feet in elevation, and farther to the south they decline gradually to the lowland area of the lake flat. The geological conditions make it apparent that the present summit is not the original surface of this range. There was an earlier generation of mountains, perhaps higher than the Oquirrh Range of to-day. The summit topography is not interpreted as a peneplain, but as the record of an advanced stage in an erosion cycle, perhaps late maturity or early old age.

Below the summit of the range there are sharp canyons, which usually have V-shaped forms. These canyons, with their tributary gulches, have become so numerous that the range is to-day dissected to the stage of early maturity. The mountain crests are narrow ridges, and in a valley bottom there is scarcely room for a roadway. The town at Bingham (see Plate XXXVIII., *B*) has but a single street, and the houses are crowded on the adjoining hillsides. The stream is covered by the roadway, and serves as a town sewer. Where a tributary joins the main there is an opportunity for another narrow road or street and for other hillside homes or mine buildings.

With what is known of the geological history of this range available it would appear that the first mountain-making movement, recorded in the folded strata, was probably pre-Tertiary. Those early mountains were subjected to erosion and a topography of late maturity was developed. A portion of that topography is now imperfectly preserved in the summit of this range, and represents in this region the work accomplished during an ancient cycle of erosion. Toward the close of that long erosion cycle the land mass of the Oquirrh Range was a lowland. The renewal of uplift produced the present mountains, and opened a new cycle of erosion. Associated with the renewal of mountain growth there may have been some faulting, but the faulting along the north half of the west front and at the north end of the range does not account adequately for the uplift of this entire range.

A. View of Bingham Canyon, looking down stream.

B. Junction of Carr Fork with Bingham Canyon, showing the upper portion of the town where there are two streets, and at the left a portion of the Utah Copper Mine.

If the range as a whole is a fault block, the line of movement of the block is now buried under the sediments in the old lake flat.

The erosion surface which was uplifted and formed the summit of the new mountain mass was at once attacked by all the agents of weathering and by the rejuvenated streams. The cutting of the present canyons was begun. This work appears to have been done by streams which were vigorous. The valleys are sharp, V-shaped notches, and it seems probable that they were cut during the moist stages of the Pleistocene period. (See Plate XXVIII.) As the waters of Lake Bonneville rose, the base to which the small streams from this range could cut was elevated. Some of the streams were ponded, and the lower courses of their valleys were filled with silts. When the lake waters sank, during an interglacial interval, these little streams were rejuvenated. They cleared away the silts and began deepening their courses. Following the last high-water stage of the Bonneville waters the Bingham Canyon has removed most of the silts deposited in its valley at the high-water stage, and reduced its bed nearly as low as it can with its present volume and the base as determined in the Jordan Valley. If all of the silts were removed about the base of this range, it is certain that the streams could dissect the mountain masses to much greater depth. In the valley of the Jordan there are at least 1,000 feet of fine deposits which are a record of alluviation during the history of closed drainage in the Great Basin.

In attempting to fix the geologic age of these physiographic events it seems probable that the old erosion surface on the summit may be of late Miocene age, and a part of that broad erosion surface which, near the close of the Miocene period, extended throughout much of western Colorado, Utah and Arizona. Extensive portions of that old erosion surface were reduced to the peneplain stage, but it is rational to believe that many other portions, especially those about the margin, may have been at the stage of late maturity when the next physical revolution or orographic movement in this portion of the continent began. Placing the summit erosion surface as late Miocene provides the Pliocene period for the uplift and deformation, and the opening

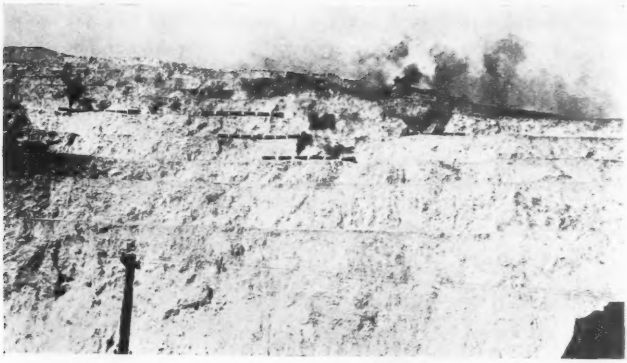
work of dissecting the modern range, and suggests the early Pleistocene as the time for the deeper cutting and last shaping of the present canyons. The canyons are certainly young, and they were certainly cut in part during Pleistocene time. They may reasonably be correlated with the great canyons of the San Juan Mountains, which are known to have been developed during and since the Pleistocene time. Some time must be allowed for mountain growth after the earlier generation of the Oquirrh Mountains were reduced to a lowland and before the cutting of the modern canyons had gone far. The necessary data for definitely fixing the geologic date of the summit peneplain has not, however, been secured.

BINGHAM CANYON ORES.

The most significant ore body in this region is at the great Utah Copper Company's mine in the mountain spur between Bingham Canyon and Carr Fork of Bingham Canyon. This mountain mass is to-day laid bare from the summit, at about 7,500 feet, to and below the roadway in the canyon. (See Plates XXXVIII., *B*, and XXXIX.) This remarkable exposure shows at many places by a dark yellow color the depth of the zone of oxidation. By closer examination the great mass of secondary ores are found to begin immediately beneath that zone, and to extend a little below the depth of the canyon. The zones of oxidation and of secondary enrichment have been found to continue into the hill across the canyon to the southeast from this great exposure. The oxidized zone is much thicker near the hilltops than on the valley slopes, and is absent in the bottom of the canyons. It appears that the streams are flowing over and cutting into the secondary ores of this mountain mass. Fig. 57 presents in graphic form the essential facts for this discussion regarding the secondary ores.

RELATION OF PHYSIOGRAPHIC DEVELOPMENT TO THE ENRICHMENT OF THE ORES.

The physiographic history as outlined above would indicate that the period during which conditions must have been most favorable for the secondary enrichment of ores was near the close



A. The uncovered body of ore in the Utah Copper Company's mine, showing several levels on which steam shovels are at work. The oxidized zone extends but a little below the surface. The great mass of ore exposed has been secondarily enriched.

B. General view of the Utah Copper Company's mine taken from the south. The crest of the range north of Bingham Canyon is shown in the sky line.

of that cycle of erosion when the summit topography was developed. The truncation of the great folded and faulted mass involved a long period of time, and when the surface was nearing to base-level the ground-water table presumably stood at a somewhat constant level for long periods of time. When there was a renewal of mountain growth and the present mass of the Oquirrh

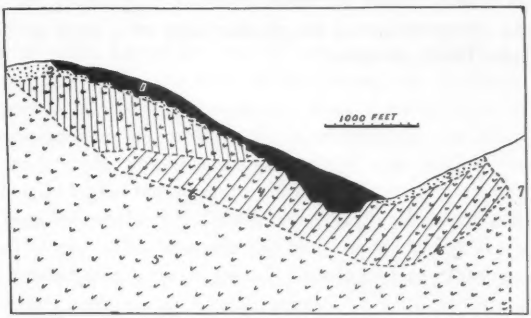


FIG. 57. Longitudinal section through central portion of ore body of the Utah Copper Company, Bingham Canyon, Utah. (1) Ore and capping removed; (2) oxidizing capping; (3) covellite ore; (4) chalcocite ore; (5) monzonite; (6) boundary of ore body developed and partially developed; (7) quartzite. (After J. J. Beeson, *Bull. Am. Inst. Min. Eng.*, November, 1915.)

Range was uplifted, the streams began at once their work of dissection. As the valleys grew deeper, the ground waters were drawn off. Oxidation proceeded to greater depths in the hilltops, and began on the valley slopes. Secondary enrichment has also continued during this later cycle, and may be in progress to-day. The amount of oxidation on these valley slopes represents the work accomplished during the time that the canyons have been developing. But the stream work has been vigorous, and the dissection has gone on into the body of secondary ores, but the oxidation has also been rapid and is present even at the stream level in the bottom of Bingham Canyon (see Fig. 57). When the Bonneville waters were at their maximum height the stream was ponded, rainfall was heavy, and the ground-water level was pre-

sumably somewhat raised. When the lake waters were drawn off the ground water in this mountain range was lowered.

A further or more detailed interpretation of the physiographic history and the relation of that history to the record of the secondary enrichment of ores must await a fuller knowledge of the shape of the ore body, and more extended field studies. Those studies should include the examination of neighboring ore bodies and the interpretation of the physiography of a large portion of the Great Basin province.

ON THE MEASUREMENT OF TEMPERATURE IN BORE-HOLES.

JOHN JOHNSTON AND L. H. ADAMS.

An accurate knowledge of the temperature gradient down through the crust of the earth, besides being very desirable from the purely scientific side, would also, there is reason to believe, be of some economic importance; for Koenigsberger and Mühlberg[1] have made it plausible that the presence of coal or oil is indicated by a locally higher temperature gradient which, if this prove to be well-founded, could therefore be used as an aid in the discovery of coal or oil. The data now available are with very few exceptions subject to a large degree of uncertainty, as examination of the results collated by Koenigsberger, or consideration of the usual mode of observation, suffices to show; for, although a large number of scattered observations of temperature in bore-holes have been made, there has been practically no extended systematic investigation of this question. Most of the work done heretofore has comprised observations—or in many instances, only a single observation—with a single maximum thermometer which was lowered to the bottom of the hole; and a temperature gradient was derived by dividing the difference between the mean air temperature at the top of the hole and the observed temperature at the bottom by the depth. This procedure would yield, even if the observations were accurate, merely the mean gradient, which is in general less significant than the individual gradients through the several strata; for these separate gradients would differ from each other in accordance with the differences in heat conductivity of the strata. Now if observations of rock temperatures are to serve any useful purpose, either scientific or technical, they most be determined more systematically and with greater accuracy than has hitherto been general. Failure to secure correct results

[1] Koenigsberger & Mühlberg, *Neues Jahrb.*, *31*, 107 (1911).

is due to two main causes: (1) that, owing to the poor conductivity of the rock and of the air surrounding the thermometer, the thermometer does not attain to the temperature characteristic of the particular rock horizon; (2) that the temperature as finally read is not an accurate measure of that attained by the thermometer. It is the purpose of the present note to point out the precautions essential to the attainment of accurate and trustworthy results, and to state the limitations of accuracy and convenience of the various methods of measuring the temperature in bore-holes.

Two main modes of procedure are possible: (1) the use of a maximum reading mercury thermometer; (2) the use of an electrical method, either resistance thermometer or thermoelement. Heretofore the first method has been used exclusively, though in general without proper precautions; it possesses the advantage that the necessary apparatus is easily transported, and does not require special technical experience. On the other hand electrical methods readily yield an accuracy ten times as good, and are much more rapid; the apparatus however may be somewhat more cumbersome and its operation requires some degree of experience with electrical measurements. We shall now take up the several methods, presenting some data which we have obtained,[2] after which we shall discuss at greater length the relative advantages of each method.

OBSERVATIONS WITH THE MERCURY THERMOMETER.

Our first experience in measuring temperatures in a bore hole was in June, 1912, at a hole, at that time about 5,230 feet deep, near Charleston, W. Va. Two types of maximum thermometers were used. One type[3] had its stem bent round so as to be par-

[2] The field work was carried out in conjunction with the U. S. Geological Survey, the members most closely concerned being Dr. David White in the earlier series of measurements, and Messrs. G. F. Becker and C. E. Van Orstrand in the last series.

[3] These thermometers belonged to, and had previously been used by the late Professor W. Hallock, of Columbia University; his published results (*School of Mines Quarterly*, 17, 148, 1897), which are given to 0.01° F., must have been taken from a curve, but no details of any sort are given in that paper.

allel to the bulb, and accordingly had an inverted scale. This type of instrument is superior in that the readings are not disturbed by jarring after the maximum temperature has been attained; but it has the disadvantage of being less compact and more easily broken and that the mercury thread is much harder to shake back in preparation for subsequent readings. There were three thermometers of this type, each enclosed in a sealed thick-walled glass tube (about 1.5 cm. diameter, 25 cm. long); in practice (following Hallock) these were protected by a jacket of thick flannel, and encased in a length of 2-inch iron pipe, closed at either end by a screw cap, which was attached to the lowering line. These conditions obviously do not make for a rapid attainment by the thermometers of the temperature of the region in which they are placed; indeed experience showed that a period of several hours would be required for complete temperature equilibrium, therefore for accurate readings. In view of these facts it is somewhat surprising that Hallock should have published his results to 0.01° F.

The other type of thermometer was straight, and rather small.[4] Three of these were enclosed together in a brass case, provided with suitable springs to prevent jarring; this case was attached directly to the lowering line.

Procedure.—The four thermometer cases—three containing each a single one of Hallock's thermometers, the fourth containing the three Taylor instruments—were lashed to a thin iron rod, which was attached to the foot of the bailer; the first trial excepted, when they were all hung inside the bailer. The bailer was attached to the sand-line, and raised or lowered by means of the engine. Depths were measured down the sand-line. The results are brought together in the following table.

Discussion of the Results.—From inspection of the following table it is evident that little definite can be said as to the rock temperature, except that at 5,230 feet it is about 54° C. But the table brings out several points of interest; in especial it indicates certain things to be avoided.

[4] Total length 15 cm. Graduated from 10–110° C.; each degree about 0.8 mm. long. Made by the Taylor Instrument Companies, Rochester, New York.

TABLE I.

RESULTS OF MEASUREMENTS OF TEMPERATURE IN THE BORE-HOLE NEAR CHELYAN, W. VA. (JUNE 21–24, 1912).

Number of Experiment.	Date.	Depth, Feet.	Period of Immersion, Hours.	Temperatures Observed.		Remarks.
				Thermometer Number.	Reading Degrees C.*	
I	21/VI a. m.	5,230 (bottom of hole)	1	H 1	48.5	Thermometers all suspended within the bailer.
				H 2	47.2	
				H 3	-----	
				1	51.8	
				2	52.0	
				3	52.0	
II	21/VI p. m.	"	3	H 1	53.4	Hole quite dry.
				H 2	48.3	
				H 3	53.3	
				1	54.0	
				2	54.0	
				3	54.0	
III	22/VI a. m.	"	1	H 1	52.3	Thermometers all lowered into water, which had been poured into the hole the previous evening. Case had broken loose: consequently the thermometers suffered considerable jarring.
				H 2	52.8	
				H 3	52.8	
				1	40.0	
				2	41.0	
				3	47.0	
IV	22/VI p. m.	4,730	2	H 1	41.3	500 feet from bottom.
				H 2	42.2	
				H 3	42.3	
				1	47.1	
				2	47.7	
				3	48.0	
V	24/VI a. m.	5,236	¾	H 1	55.5	Temperatures taken after drilling had been resumed and continued for about 6 hours, and proceeded for about 6 feet.
				H 2	54.0	
				H 3	56.7	
				1	all broken	
				2		
				3		

Subsequent experience has demonstrated that a period of immersion of 3 hours in air is ample for the practical attainment of

*Two of Hallock's thermometers were graduated in degrees Fahrenheit; their readings have been converted to Centigrade, for the sake of clearness. It may here be remarked that none of the thermometers had, owing to special circumstances, been calibrated; but in view of the uncertainty attaching to the above readings anyway this ignorance of the (probably small) corrections does not matter.

the true temperature by a thermometer enclosed only in a brass case; so that the temperature at 5,230 feet should be close to 54°, according to experiment II. This shows that a period of 3 hours even is insufficient for proper results with the arrangement adopted by Hallock; and number IV. shows that with his outfit immersed for only 2 hours very serious errors may result. Nos. II. and IV. together indicate that the temperature gradient at 5,000 feet is somewhat in excess of 1° C. per 100 feet.

Comparison of No. III. with No. II. shows that water, even after standing all night in the hole, had not attained the proper temperature; for one hour's immersion in water would seem to be sufficient, even with Hallock's outfit. It is unfortunate that in No. III. the other thermometers gave false readings due to jarring while they were being raised; but this experience demonstrated the necessity of providing some weight at a distance below the thermometer case, in order to prevent the latter from being jarred against the sides of the hole. The same misfortune happened in No. 5, but in this case the case had received such a severe shock that it was partly deformed and all the thermometers inside it were smashed. The readings of the three Hallock thermometers must be much too low by reason of the short period of immersion, but they show very decidedly that a great rise of temperature of the surrounding rock was produced by a few hours' pounding of the drill.

From these results, then, it follows that two points with respect to the time for making temperature observations must be remembered: namely, that trustworthy determinations can not be made until considerable time (at least 24 hours, probably longer) has elapsed since drilling was done or since a considerable body of water was poured into the hole.

The experience gained in the foregoing measurements was made use of in planning for the next series. These observations, which were made in a bore hole near Findlay, Ohio, in November, 1912, will be discussed very briefly here, since an account of them has already been published.[5] In this instance the tempera-

[5] Johnston, *Am. J. Sci.*, *36*, 131 (1913).

tures were measured by means of straight maximum thermometers[6] which, with a scale extending from 0°–100° C., were divided into single degrees, the length of each of which was about 1.4 mm.; they could be read to 0.1° C., which is the limiting accuracy of maximum thermometers under any circumstances. Now if only a single thermometer is used, accidental jarring of the thermometer sustained while it is being raised to the surface may lead to errors the existence of which might not be detected; in order to minimize this possibility of error, three thermometers were always used together. As a matter of fact the readings of all three thermometers were in each case concordant, showing that freedom from jarring was attained by means of the thermometer cage made use of. This cage consists essentially[7] of a thin-walled open copper tube, slightly constricted at the lower end, suspended between two spiral springs which were fastened to a sort of cage made of stout wire; this in turn was attached top and bottom, by means of open links, to 100-foot lengths of ⅛-inch steel wire cable. The lower thin steel cable carried a weight; the upper was attached to the bottom of the bailer, which in turn hung as usual on the sand line and was raised and lowered by means of the engine. The use of a weight is necessary, as in its absence there is likely to be considerable jarring of the thermometers; the weight must of course be so far from the thermometers that the heat absorbed by it is not abstracted from the zone the temperature of which is desired. Similarly with the bailer, which is a convenient means of minimizing any convection currents which might perchance be present.

The observations are presented in Table II. The first observations were made at a depth of 1,165 feet, the thermometers being left at that level for 1½ hours in a first trial, and for 1 hour in a second; the concordance of the results thus obtained shows that, with the form of apparatus used,[8] errors due to jarring of

[6] Obtained from H. J. Green, 1191 Bedford Avenue, Brooklyn, N. Y.

[7] The apparatus will not be described at length, because Mr. Van Orstrand has devised and tested out a modified form of thermometer-holder for this purpose which will be described in detail in the near future.

[8] The period required for the practical attainment of temperature equi-

the thermometers had been eliminated, and that a period of 1¼ hours sufficed substantially for the attainment by the thermometers of the temperature of the zone in which they were placed. This is confirmed by the agreement between the measurements made with a period of 1¼–1½ hours and those in which the thermometers were left overnight in the hole; as is evident from the figure, in which temperatures have been plotted against depths.

TABLE II.

TEMPERATURE AT VARIOUS DEPTHS IN THE BORE-HOLE AT FINDLAY, OHIO.

Depth in Feet.	Period of Immersion of Thermometer, Hours.	Temperatures Observed.		Corrected Average Temperature	
		Thermometer Number.	Reading, Degrees C.	Centigrade.	Fahrenheit.
100	18	1	11.0	11.0	51.8
		2	11.0		
		3	11.0		
550	1.25	4	13.0	13.1	55.6
		5	13.2		
		6	13.1		
770	1	4	14.5	14.5	58.1 (level of gas in flow)
		5	14.6		
		6	14.5		
1,165	1.5	4	19.4	19.5	67.1
		5	19.5		
		6	19.6		
1,165	1	4	19.3	19.4	66.9
		5	19.4		
		6	19.5		
1,900	1.25	1	22.5	22.5	72.5
		2	22.5		
		3	22.4		
2,650	1.25	4	25.4	25.5	77.9
		5	25.5		
		6	25.6		
2,800	1.5	1	26.5	26.5	79.7
		2	26.5		
		3	26.4		
3,000	18	4	27.8	27.8	82.1
		5	27.9		
		6	27.8		

librium between thermometers and the surrounding rock depends of course upon the form and weight of the cage surrounding the thermometers, and should always be determined by actual trial.

This figure shows very plainly the general regularity of the results, apart from the marked discontinuity which was observed, as might be expected, at the point at which gas appears. The temperatures observed at depths less than 770 feet do not represent the temperature of the surrounding rock, but that of the atmosphere in the well, which is cooled by the flow of gas, between the outer and inner casing of the well.

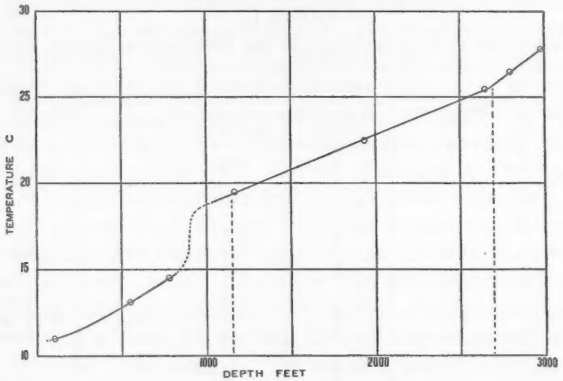


FIG. 58.

OBSERVATIONS WITH AN ELECTRICAL RESISTANCE THERMOMETER.

In the measurement of temperature by electrical means, two main methods are available—the thermoelectric and the resistance method respectively—each of which possesses certain advantages not shared by the other.[9] For the first trials it was decided to have recourse to a resistance thermometer; the most convenient form of which for the purpose in hand is a coil of nickel wire enclosed in a suitable manner. Accuracy with a resistance thermometer requires that the resistance of the leads be compensated; consequently it is necessary to provide a cable[10]

[9] Their relative merits are discussed later.

[10] The other method of compensation requires four wires, all of copper and well insulated; consequently it would involve the use of a much heavier cable, since there would have to be at least one steel wire to insure that the cable should bear its own weight without damage.

containing at least 3 wires, 2 of which must be of copper, well insulated from one another and protected against possible damage from the outside.

DESCRIPTION OF THE APPARATUS USED.

The resistance thermometer coil, of nickel wire, has a resistance of 250 ohms, and consequently a temperature coefficient of about 1 ohm per degree C.; it is enclosed in a brass tube, about 30 cm. long and 1 cm. diameter.[11] The thermometer case was filled up with fusible alloy, so as to prevent damage by crushing if it were used in wells containing liquid;[12] but even if the thermometer is to be used only in dry holes, this alloy filling is probably advisable by reason of its beneficial effect with respect to the time lag[13] of the instrument. The measuring apparatus—bridge and galvanometer—was of temporary character, made up of instruments which happened to be available; it will therefore not be described,[14] except to state that readings to 0.01 ohm (=0.01° C.) could be made with ease and certainty. In order to enable one to detect any lack of constancy of the measuring apparatus—such as might result from dirt, faulty connections, etc.—a test coil of 250 ohms was made up and enclosed in appropriate manner; its terminals could be attached to the terminals to which the wires of the thermometer cable normally go. Readings with this test coil were made at intervals; they proved to be absolutely constant. This precaution is always advisable, if for no other

[11] This thermometer was obtained from the Leeds and Northrup Co., 4901 Stenton Avenue, Philadelphia, Pa.

[12] With regard to the usefulness of observations in wells filled with liquid, see *postea*.

[13] Filling with naphthalene (which moreover is an electrical insulator) would probably be about equally efficacious.

[14] In general, one would have recourse to the maker of the resistance thermometer, who would specify, or supply, the measuring apparatus required for any prescribed degree of accuracy. It may be mentioned that a portable galvanometer is now on the market by means of which one could read the temperature attained by the thermometer coil with a precision of 0.002°; but it is another matter to insure that the thermometer temperature corresponds to the real temperature of the rock within a limit several times as great as the precision of the instrument.

reason than that its use aids one greatly in locating the source of any electrical troubles which may arise.

The Cable.—The cable, 2,500 feet in length, was made[15] in accordance with the following specifications:

2 conductor No. 20 B. & S., each conductor made up of 10 No. 30 B. & S. bare soft copper wires, cotton wound, insulated with at least 1/32″ wall, 30 per cent. fine Para rubber, conductors separately braided, and laid up with two steel supporting strands each consisting of 19 No. 25 B. & S. special high tensile tinned steel wires, each strand to be cotton wound and provided with a suitable soft cotton braid so as not to cut into the insulation of the conductors, the four conductors making up the cable to be twisted with a suitable lay without any jute filling and provided with two stout linen braids over all saturated with a moisture-repelling compound.

The diameter of this cable is about ½ inch, its weight 220 lbs. for the 2,500 feet. Its electrical qualities are excellent; for there is an insulation resistance between the two steel wires of 710,000 ohms, and between the two coppers or either copper and steel of 20 megohms or more. The cable has so far suffered no noticeable deterioration.

The weight of the cable[16] is the draw-back of this method; it could probably be reduced somewhat. If such reduction of weight is attempted, it should not be by reducing the size of the copper wires[17]—for their total weight is but 15 lbs. for the 2,500 feet—but by using less steel, and, possibly, less insulating material. The steel in the present cable weighs about 95 lbs., and should easily be able to support a weight of 1,000 lbs.; so that a considerable reduction is possible without an undue sacrifice of safety. An appreciable reduction of the amount of insulation

[15] By the Safety Insulated Wire and Cable Co., 114 Liberty St., New York.

[16] In this preliminary trial we endeavored to make certain that the method should not be unsuccessful by reason of a failure of the cable in any respect; and so a large factor of safety was allowed.

[17] Such reduction is of itself inadvisable because possible inequalities, as between the two leads, will cause greater percentage errors in the measured resistance—hence in the temperature derived therefrom—the smaller the copper wires.

material, which has a gross weight of about 90 lbs., would be attended with some risk; probably no manufacturer would make such a cable except at the risk of the buyer. It may be pointed out that, if a cable longer than 2,500 feet be desired, the required length of a lighter cable (containing fewer steel wires) can be made and attached to the lower end of the present cable, which is strong enough to support the total weight.

The cable was attached at its lower end to the thermometer, the appropriate wires being soldered together and thoroughly taped; its upper end was fastened to three brass binding screws, set in a block of hard rubber, which in turn were connected by a short (6 feet) length of cable to the binding screws on the Wheatstone bridge.

Apparatus for Raising and Lowering the Thermometer.—This consisted essentially of two parts—a winding drum, about 3 feet diameter, operated by hand, and a frame supporting a guide wheel over which the cable passed and in so doing recorded continuously the depth attained by the thermometer.

The construction of a suitable drum is no simple matter, because of the considerable stresses involved when the cable weighs 200 lbs. Every effort was made to secure lightness, but in spite of all, the drum and frame weighed several hundred pounds. No description of its construction will be given, because its operation proved rather unsatisfactory; indeed we found that hand operation would hardly be practicable at all under the circumstances. Accordingly the cable was wound off on to the bull-wheel, which was operated by the engine; this admits of much more rapid raising and lowering of the thermometer, and is decidedly preferable wherever possible.[18]

The construction of the frame supporting the guide wheel is evident from Fig. 59. Into the frame *AB*, which is triangular in order to secure lateral stability, is pivoted the framework sup-

[18] If a cable is to be repeatedly wound and unwound, the diameter of the drum should be 30 times that of the cable; in the present instance, therefore, 15 inches. The use of a smaller ratio might perhaps be admitted in this instance, especially in view of the very great saving of time if the engine is used.

porting the wheel; this arrangement ensures that the cable enters the hole centrally, independent of the momentary position of the coil on the winding drum. The circumference of the wheel is exactly 8 feet; eight projecting teeth are fastened so as to engage the toothed wheel of a revolution counter *D* which therefore records directly the depth in feet. This method of measuring the

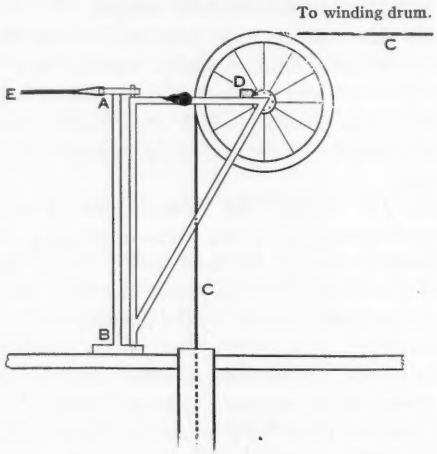


FIG. 59. *AB*, triangular frame, seen end on; *CC*, cable; *D*, counter; *E*, rope (tightened up by means of a twister) attached to a rigid support.

depth proved very satisfactory, for on pulling up the thermometer after it had been down 2,500 feet the reading returned accurately to zero; this of course is to be expected because the stretch of the cable takes place *between* winding drum and guide wheel.

In order to keep the thermometer approximately central in the hole and to ensure its descent, a light (1/8 in.) steel cable, 100 feet long, carrying a weight of about 10 lbs., was attached to the cable just above the thermometer.

Scheme of Electrical Connections.—This is obvious from Fig.

60. It may be remarked that the magnitude of the resistance *AB* should be so chosen as to have the readings on the bridge wire as far apart as is consistent with the range of temperatures to be measured. The lead to the battery consisted of the two groups of steel wires in parallel. The resistance of the 2,500 feet of copper leads proved to be 26.84 ohms; that of the bridge wire about 20 ohms. From a series of observations of the bridge reading corresponding to certain standard resistances, combined with the constants of the bridge circuits, the resistance measured was expressed as a function of the bridge reading.

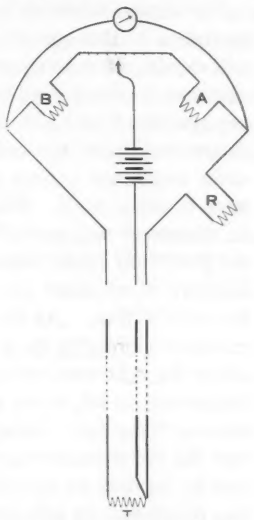


FIG. 60. Diagram of bridge connections. *AB*, ratio coils, 200 ohms; *R*, balance coil, 250 ohms; *T*, thermometer coil, 250 ohms.

Calibration of the Thermometer.—The resistance thermometer (attached to the cable and ready for use in the field) was immersed in a *well-stirred* large water-bath, kept constant at a series of temperatures which were determined accurately by means of a standard mercury thermometer; and the bridge readings observed. The formula connecting bridge reading with resistance was combined with the second degree equation

$$r = A + Bt + Ct^2,$$

which expresses the resistance of pure nickel as a function of the temperature; the constants *A*, *B* and *C* were determined by least squares from the observations. The equation obtained in this way reproduced the observations with a probable error of about 0.02°; from it we constructed a table giving the temperature for even readings on the bridge; the temperature differences proved

to be nearly constant,[19] varying only from 0.055° to 0.059° per division over the range 0–50° C.

It is always advisable to know the lag of the thermometer, for by means of this quantity one can tell how long the instrument will require, after being exposed to a given rise (or fall) of temperature, to reach equilibrium with the new temperature within any specified limit; with an electrical thermometer the lag can be determined in the bore-hole, preferably however in the laboratory under conditions as close as possible to those likely to be encountered in actual work. For this purpose a cylindrical can (about 8 in. diameter) was partially immersed in a thermostat at 25.00°, the previously cooled thermometer lowered into it (with adequate dampers to minimize convection) and readings taken at known intervals of time. As thus measured, the rate at which this thermometer approaches the true reading proved to be[20] $\Delta\theta_t = \Delta\theta_0 e^{-t/7}$, where the difference between its momentary reading and the true temperature is $\Delta\theta_0$ at any specified moment and $\Delta\theta_t$ at the end of t minutes thereafter. Actual observation in the bore-hole showed that the thermometer was within about 0.8° of its final temperature by the time the operation of raising or lowering it to position was completed; by substituting this value of $\Delta\theta_0$ in the above formula, we find for $\Delta\theta_t$ the values (*a*) 0.19_5, (*b*) 0.09_4, (*c*) 0.04_6, (*d*) 0.01_1 after (*a*) 10, (*b*) 15, (*c*) 20, (*d*) 30, minutes respectively. Actual observation yielded the results (*a*) 0.18°, (*b*) 0.08°, (*c*) 0.04°, (*d*) 0.01°, which agree, within the limits of error, with those calculated. This shows therefore that the time lag predetermined in the laboratory under comparable conditions can be made use of to save time in the actual observations, that one need not wait each time until $\Delta\theta_t$ is 0.01°; it suffices to take two or three readings at known intervals—*e. g.*, 10, 15, 20 min-

[19] With a slide-wire bridge this can always be secured by a proper choice of resistances (see C. F. Marvin, *Phys. Rev., 30,* 522 (1910)); but the opposing curves do not compensate with the most suitable bridge in which the balance is secured by changing the resistance in one arm only.

[20] This means that the time lag of this thermometer, when surrounded by air inside a cylindrical vessel about 8 in. diameter, is 7 minutes; if the thermometer were immersed in water the time lag would be reduced probably one hundred fold.

utes,—after the thermometer is in position, whence one is enabled to calculate the small correction to be applied in order to obtain the proper final temperature. In the measurements as actually carried out the thermometer was left in position at each depth for at least 20 minutes, and in several cases for 30 minutes or more; the final results, corrected for lag and transformed to temperatures by means of a second calibration performed since the return of the apparatus from Mannington, are brought together in the following table:

TABLE III.

TEMPERATURES IN THE HIBBS NO. 4 WELL NEAR MANNINGTON, W. VA., AS DETERMINED BY THE ELECTRICAL RESISTANCE THERMOMETER.

Date.	Time of Final Reading at Each Depth.	Depth, Feet.	Temperature Corrected, Degrees C.	Remarks.
Oct. 6	11.30 a. m.	0	16.00	Air temperature.
	11.55	100	13.36	
	12.30 p. m.	504	14.18	
	12.55	1,000	17.72	
	1.20	1,501	20.36	
	1.56	1,998	22.82	
	2.25	2,500	26.07	
	2.50	2,250	24.20	
	3.20	1,750	21.49	
	3.45	1,250	19.15	
	4.15	749	15.92	
	4.40	248	12.71	
Oct. 7	8.00 a. m.	500	13.89	Thermometer ieft over night at this depth.
	10.10	1,002	17.70	In all of these readings there were four dampers of sheet rubber, respectively 10 and 20 feet above and below the thermometer.
	10.45	1,501	20.33	
	11.10	2,001	22.85	
	11.40	2,500	26.09	

These results are plotted in Fig. 61, which shows the good concordance of the two series of experiments; indeed this agreement to about 0.02° is even better than one would expect. It is apparent that time enough was given at each depth, for there is no systematic deviation between the readings taken at a series of increasing depths (and temperatures) and those at decreasing depths. Moreover the presence of dampers makes no appreciable difference on the temperature observed, except at 500 feet where the thermometer remained overnight; but this is precisely what one would expect, since the dampers, to be effective, must remain in position long enough so that the rock may regain by conduction

its true temperature, which had been changed by any convection currents that were present.

The final mean results, arranged according to increasing depth, are brought together in Table IV., to which are appended the re-

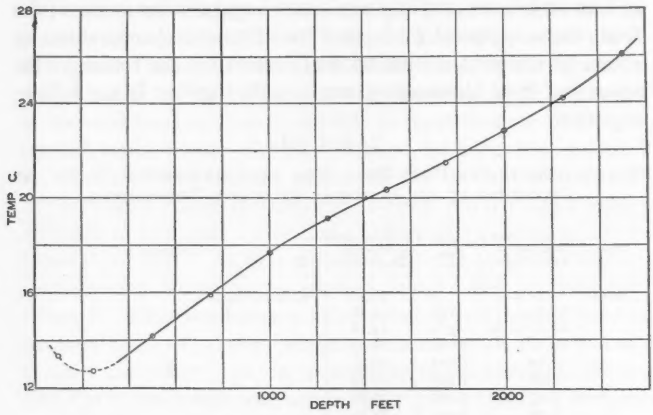


FIG. 61.

sults obtained quite independently by Mr. Van Orstrand,[21] working October 9–11 with mercury thermometers in brass cases. The agreement between the two series is all that could be expected, at depths greater than 1,000 feet; at the lesser depths there must have been some systematic error in the results obtained with the mercury thermometer.[22]

GENERAL REMARKS ON THE SEVERAL METHODS.

The chief advantage of mercury thermometers is the ready portability of the necessary outfit; indeed wherever the sand line is available as a means of lowering the thermometers, the abso-

[21] We wish to express our indebtedness to Mr. Van Orstrand for permission to use his data here.

[22] It is significant that divergence occurs where the temperature is lower than the prevailing atmospheric temperature at the surface.

TABLE IV.

FINAL MEAN RESULTS FOR THE HIBBS NO. 4 WELL.

Depth, Feet.	Temperature, Degrees C.		Difference.
	Measured Electrically.	As Read on Mercury Thermometers (Van Orstrand).	
100	13.36.	12.0	+1.4
250	12.71	12.3	+0.4
500	14.16	13.7	+0.4
750	15.93	15.6	+0.3
1,000	17.71	17.5	+0.2
1,250	19.15	19.0	+0.1
1,500	20.34	20.3	0.0
1,750	21.49	21.5	0.0
2,000	22.84	22.9	−0.1
2,250	24.20	24.1	+0.1
2,500	26.08	26.0	+0.1

lutely essential equipment need weigh but a few pounds. The use of such thermometers would thus be advisable for reconnaissance work over a large area, especially where this work is to be participated in by a number of observers, since it requires less previous technical experience than the other method. On the other hand, the precision attainable with maximum thermometers is at best $\pm 0.1°$ C., a degree of precision which, while it enables one to secure reasonably good temperature gradients over a large range, is insufficient to determine the reality of small differences of gradient in comparatively thin strata. Moreover the results are somewhat uncertain whenever the temperature to be measured is not sensibly above the air temperature at the top of the hole; and this lack of certainty is not entirely eradicated even if the thermometers are immersed in ice-water immediately upon withdrawal from the hole. The other great drawback of mercury thermometers is their slowness when encased, as they must be, in some sort of metal case, constructed so as to minimize jarring; for in dry holes, even under the most favorable conditions, a period of at least an hour is required before one can be assured that the reading of the thermometer corresponds to the temperature of the rock at the horizon in question. Thus the measurement at each depth would require 1½ hours, even when duplicate groups of thermometers are available. This disadvantage indeed may

in part be obviated by the use of several thermometer cases, attached to the lowering line at different levels; but the lack of precision of the readings is a circumstance much less easy to change.

The electrical resistance thermometer, on the other hand, readily yields readings with an uncertainty of but 0.01° C., or ten times as good as is obtainable with maximum reading mercury thermometers; moreover it is, as we have seen, much more rapid, each reading requiring only 20–25 minutes, an interval which could undoubtedly be reduced somewhat. The apparatus is however somewhat cumbersome, and its use requires greater technical knowledge—for instance, ability to find and repair on the spot any electrical troubles caused by breaks, poor connections, or otherwise. Consequently this apparatus can not be put into unskilled hands; a mercury thermometer, on the other hand, will yield fair results with a modicum of knowledge and care. But wherever accuracy is required—and for scientific purposes, at least, such readings are now practically useless unless they are in fact accurate—an electrical method is far preferable; moreover since readings can be made continuously and since the reading can be approached either from a lower or higher temperature (the latter being impossible with maximum thermometers), one can be assured of the accuracy of the reading in far shorter time[23] and with much less labor. For instance, one could not reliably ascertain, except by an electrical method, the temperature gradient through a comparatively thin rock stratum, a determination which is important because it is the best means of determining the relative heat conductivity of the various strata; moreover it would enable one to detect any abnormal production or absorption of heat at any level, an occurrence which could well pass undetected if maximum thermometers only were employed.

A thermoelectric thermometer could also be used; and it could be made to possess the advantage of reaching and registering the final temperature within a much shorter interval of time. The

[23] This time can be still further reduced by taking readings at known intervals and extrapolating to the final value by means of the curve showing the lag of the instrument under the particular conditions (see p. 756); this procedure is, of course, impracticable with mercury thermometers.

best thermocouple to use would be copper-constantan, which gives about 50 microvolts per degree, so that with even a single element one could, using the best form of portable galvanometer, read to 0.1°. To insure constancy of temperature of the cold junction one would immerse it in a mixture of ice and water contained in a small Dewar flask; this could either be lowered into the hole or kept at the surface. In the former case, the thermoelement proper[24] would be 2–3 feet long, and there would be two copper wires leading up to the measuring instruments at the surface; in the latter case both the copper and constantan[25] wires of the element extend to the surface where the junction between the end of the constantan wire and a second copper wire (forming one of the leads to the instruments) is immersed in the ice-bath. In either case the cable would consist of only two insulated wires,[26] and hence could be made lighter than is possible with a resistance method; moreover, in place of the rather expensivse bridge required for the latter, a much less expensive potentiometer suffices for the thermoelectric method. The temperature gradient could also be measured directly by means of a thermoelectric method; thus a 10 junction element, 100 feet long, would enable one to measure the gradient in 100 feet to 0.01° C., and would require again only a two-conductor cable and, in this case, no potentiometer at all since readings could be directly as the scale of the galvanometer. Or one could combine the multiple element (giving the gradient to 0.01°) with a single element (giving the temperatures to 0.1°), and require only a three-conductor cable; such an arrangement however would have no advantage over the resistance thermometer except that the time required for the attainment of the true temperature would be somewhat shorter.

[24] It could perfectly well be made of a number of junctions in series; this would enhance the sensitiveness which, with a given galvanometer, is proportional to the number of junctions.

[25] The ordinary objections to a lead-wire of constantan do not apply here, for the temperature in bore-holes is really so uniform that errors due to inhomogeneities in the wire are here absolutely negligible.

[26] Except where no depth greater than 1,000 feet is to be investigated, it would be necessary for strength to have a steel wire included in the cable; for neither copper nor constantan will support with safety a much greater length of themselves when properly insulated.

To sum up the discussion of the relative merits of different types of thermometers for measuring temperatures in bore-holes. The best possible accuracy with maximum reading mercury thermometers is $\pm 0.1°$ C.; the accuracy actually attained is in general less than this, especially wherever the rock temperature is not sensibly greater than the prevailing air temperature at the top of the hole. Mercury thermometers possess the advantages that the outfit required is readily portable and that no special previous experience is required; their greatest disadvantage, apart from their lack of accuracy, is the slowness with which they, when protected satisfactorily against jarring, reach the final temperature, and the circumstance that the thermometer must not be exposed to a temperature higher than the temperature to be measured. In comparison with this, the use of an electrical method enables one to improve the accuracy tenfold, and at the same time to cut down to one third or less the time required for an observation, and the final reading may be approached either from above or from below; the apparatus required, on the other hand, is somewhat cumbersome, and its operation calls for previous experience with electrical measurements. As between the resistance thermometer and the thermoelement, the former is probably in general somewhat more reliable for the purpose under discussion; but the thermoelement might be preferable, since the equipment required is lighter and less expensive, and since it can be made of any desired degree of accuracy.

GENERAL REMARKS ON THE OBSERVATION OF TEMPERATURES IN BORE-HOLES.

It is useless to have an accurate method of temperature registration unless conditions are chosen such that the temperature registered by the thermometer is that of the adjacent rock; nor has the latter temperature much significance unless it really represents the rock temperature at that particular horizon. Now it is obvious that a temperature measured in a hole in which there is even a small flow of water or oil can not be interpreted satisfactorily; and the same is true of a flow of gas, which on expanding

cools itself off and chills the walls at higher levels to a degree which can not be rigidly specified, so that at horizons above that of the gas in flow the measurements do not represent the temperature of the rock. It seems probable even that steady convection currents of air[27] will make the rocks at the higher levels appear warmer than they are; and this effect can not be obviated by the use of dampers unless the dampers (and measuring apparatus) be left in position for a period (several hours, probably) long enough to enable the rock to attain temperature equilibrium by conduction of heat. The last named uncertainty is probably not more than a few tenths of a degree, and without serious effect on the mean gradient; but there are gross errors (apart from instrumental errors) which have not always been avoided. For instance, it is useless to observe the temperature at the bottom of a hole until at least 24 hours have elapsed since drilling was discontinued or since water was poured in the hole; otherwise one can not be certain if the temperature observed really represents that of the rock. Moreover the temperature of water brought up by the bailer is no certain criterion of the temperature down below, for if the bailer is raised quickly, the friction against the casing may be sufficient—in deep wells, especially—to produce a temperature actually higher than that obtaining at the bottom of the hole.

A few practical points may now be mentioned, applicable no matter what method of determination is made use of. It is of little use to make observations in any hole in which there is a flow of gas or oil, or in any hole immediately after drilling has been discontinued, since the readings can not be interpreted usefully. There should be a weight not less than 50 feet below the thermometer[28] supported by a light cable; in addition to this it is advisable to fix diaphragms close to the thermometer as a means of keeping it central in the hole. The thermometer must be left long enough at each depth to insure that it had attained the proper temperature: the necessary interval can be ascertained in advance

[27] For a similar reason most of the temperatures taken in mines are of little use considered as rock temperatures.

[28] Which in turn should hang at least 50 feet below the bailer to which it is in many cases convenient to hang the apparatus.

by measurements of the rate at which it approaches the final temperature, carried out in the laboratory under conditions approximating to those which actually obtain. With electrical thermometers one can make readings at a series of diminishing depths and temperatures, and this is advisable as a check on the others; they should occasionally be calibrated with all conditions as similar as practicable to those encountered in the actual observations. When mercury thermometers are used, they should always be in groups of three, enclosed in a suitable case designed to reduce jarring; the reading is unsatisfactory if the greatest difference between the (corrected) readings of the three exceeds 0.3°.

SUMMARY.

A systematic and accurate investigation of temperature gradients within bore-holes is desirable because it would yield information as to the relative heat conductivity of different strata, and also, there is reason to believe, be of some economic importance. Such an investigation would however be of little use unless the accuracy of the observations were better than has hitherto been customary. In the foregoing pages we discuss several methods, present some new results obtained with an electrical resistance thermometer, and point out some of the precautions which must be observed. It appears that the mercury thermometer cannot yield results with an uncertainty less than $\pm 0.1°$ C., that it is not absolutely trustworthy unless the temperatures to be measured are higher than the prevailing air temperature at the surface, and that the attainment of even this accuracy requires an exposure of more than an hour at each horizon. In comparison with this, the accuracy of the electrical thermometer is ten times as good, and the time required for an observation is not over one third as long; the necessary apparatus is however somewhat less easily portable and its operation requires some degree of previous experience with electrical measurements.

GEOPHYSICAL LABORATORY,
CARNEGIE INSTITUTION OF WASHINGTON,
WASHINGTON, D. C.,
September 6, 1916.

DISCUSSION

This department has been established by the editors in order to afford to those interested in questions relating to economic geology an opportunity for informal discussion. Contributions are cordially invited either in the form of discussion of more formal papers appearing in earlier numbers or bearing upon matters not previously treated. Letters should be directed to the Editor, Sheffield Scientific School of Yale University, New Haven, Conn. The full name of the author should be attached to all communications.

Sir: As subscriber of the ECONOMIC GEOLOGY I am always reading with great interest the "Scientific Notes and News" of your journal. The following might give you some information for this column about some practical geological work, which is done at present in Switzerland.

During the mobilization of our army the geologists, instead of serving with their units, are attached to the hygiean section of the general staff of the army. Under the direction of myself as chief geologist of the general staff geological investigations of all the springs which are used for water supplies are made, so that those which are under contamination can be avoided and so in consequence a lowering of the typhoid rate may be reached. All the springs are noted on maps 1:25,000, numbered and fully described also in their relation to the geology. These investigations are not only of practical but also of scientific interest, as we are collecting in this way a lot of material for comparison as regards to the occurrence of springs.

DR. R. SCHIDER.

REVIEWS

Principles of Oil and Gas Production. By ROSWELL H. JOHNSON and L. G. HUNTLEY. New York, John Wiley & Sons, Inc., 1916. Pp. xv + 371, with 135 figs. Cloth 6 × 9.

This is probably the most comprehensive treatise on the geology and methods of producing petroleum and natural gas, which, up to the time of its publication, had appeared in this country, yet on the whole it is a most disappointing volume. The modes of occurrence of oil and gas in nature and the principles used in locating them are treated in chapters 1 to 10 and also chapter 20; the drilling of wells and the methods used in getting the oil and gas out of the ground are discussed in chapters 11 to 19 and 21; the oil and gas fields of North America are briefly described in chapter 22; and in chapter 23 a few remarks are made concerning the petroleum market with its possible tendencies in the future.

Many good and pertinent ideas are discussed in the volume. One of these—the "shape and texture" of the oil and gas reservoirs—is dwelt upon at great length and is probably over-emphasized so far as it concerns most oil and gas fields. This is a decided reaction from the generally accepted idea that rocks folds control the accumulation of petroleum and natural gas. Many of the subjects treated are stimulating to thought and reason, and if they were only well handled and the text well written, the volume would find widespread use, and would be almost indispensable to any one interested in the petroleum and natural gas industry. In view of the fact that such a work is needed, it is regrettable that the present volume shows neither deliberate consideration nor painstaking work. The arrangement of ideas is generally illogical, the writing shows great carelessness, and the reference notes are neither full nor complete. The errors and shortcomings of the volume are so numerous and noticeable that they almost obscure the many good points which are present, for even a trained geologist familiar with petroleum and natural gas literature can follow the discussions only with difficulty. It is almost a hopeless task even in an extended review to select such of these defects as will indicate the laxity which apparently attended the writing of the book. The first chapter more than any other in the book of this type should be written with the viewpoint of the reader constantly in mind, for it is this first chapter which often is the "make" or "break" so far as a prospective reader is concerned. He should expect to be told

in a generalized and untechnical way (*a*) what petroleum and natural gas are, (*b*) where and how they are obtained, (*c*) what they are used for, and (*d*) how important they are economically. Besides this he may expect to find a brief historical sketch which would add considerable interest, and perhaps a few statistics showing the growth and present size of the industry.

Is this or any similar treatment followed in the volume under discussion? Let us see. On pages 1 and 2 petroleum and natural gas are defined chemically (surely a novice desires to know more than this), and the subjects of casing-head gas, gasoline, and the price of Cushing and Pennsylvania crude under abnormal market conditions are introduced. On page 3, under the heading "Gravity," one would expect to find out something of the specific gravity of petroleum and perhaps something of the prevalent use of the Baumé scale, but nothing of this nature is mentioned. Instead, such irrelevant matters as the "new competition with coal as a fuel" and the anomalous prices of various grades of oil under abnormal market conditions are interjected. This is followed, on pages 5 to 10, by a comparison of fuel oil (in many places a refinery product) and coal as to their relative efficiency for steaming and power purposes. This in turn is followed by a heading, "Gasoline content," under which nothing is said as to the quantity of gasoline which may be obtained from various grades of petroleum, but instead there is a short discussion to the effect that the gasoline content should be the determining factor in grading different crudes. The general discussion of natural gas, on pages 12 to 16, is considerably better than the treatment of petroleum, but even here there is much to be desired. Fig. 16, on page 15, which pertains to the relative values of the production of petroleum and natural gas during a series of years, is wholly wrong, and its title does not apply to the erroneous values given in the figure. Surely this is not the way the subjects of petroleum and natural gas should be introduced in a treatise on these fuel substances.

The authors have a tendency to make statements in such a way as to confuse the reader. This is well exemplified in such expressions as "during the recent period of low prices" without the date being given, which appears near the middle of page 5, and in the title to figure 13 on page 11. The market price of petroleum changed so rapidly since these statements were written that they are out of date at the time of this review (October, 1916) only a few months after the book was issued. The use of "recently" at the bottom of page 3, and the citation of forty-cent Cushing crude on page 2, without giving the date, are similar crudities. It is true that the date of the authors' remarks could be determined by referring to the preface, but how unnecessarily awkward this would be for the reader.

On page 63, and elsewhere, the term "geologic surface" is used many times. The reviewer can not recall ever before having seen it. The authors should at least have defined the term, or if the reviewer has correctly interpreted its meaning, they might have avoided adding to the terminology by using a simple phrase, as "surface of a rock bed" or the old and more specific term "stratigraphic horizon," which has a similar meaning.

The significance of the contours in Figs. 33, 34, and 35 must be inferred from the titles. The elevations which the contours represent are not given, nor is the contour interval indicated. A legend is given for Fig. 35 and an explanation for 34, but neither legend nor explanation is given for Fig. 33, for which discrimination there is no apparent reason. Further the symbol for water as given in the legend for Fig. 35 is not to be found in the illustration.

Even the title of the volume is open to criticism, especially the abbreviated form "Oil and gas production," which appears on the cover. One is apt to expect it to be a statistical volume instead of a treatise on the geology and methods of producing petroleum and natural gas. The use of the unlimited terms "oil" and "gas" may also be somewhat misleading, and the authors appear to admit this on pages 1 and 2, where, instead of defining "oil" and "gas," they define and use the terms "petroleum" and "natural gas."

To point out a few typical references which show how incomplete they are, and with what little care they were cited, the following are here given:

Page 2, lines 26 and 27. The United States, but not the United States Geological Survey, is given the credit for mineral resources.

Page 21. A rather extended quotation from Dalton is given, but the publication in which it appeared is not mentioned.

Near middle of page 24. Reference is made to the Bulletin of the American Institute of Mining Engineers. It is preferable, where possible, as in this case, to refer to the *Transactions* of this organization, in which the discussions of the paper also appear.

At the bottom of page 34. Bell is cited, but the reference which belongs here does not appear until three pages later.

Footnote on page 39. Buckley's report on the "Building and ornamental stones of Wisconsin" is cited, but that it is a Wisconsin Geological and Natural History Survey publication is not mentioned.

A helpful feature by which a reader may determine the up-to-dateness of a reference is the date of its publication. It is given in some cases in this volume, but its absence from most of the references is very marked.

The shortcomings which have been pointed out represent but a small

percentage of those which exist in this volume. Although only a few have been cited, they are sufficient to indicate hasty and careless writing, and the absence of critical reading by persons competent to suggest and enforce such drastic revisions as would have been necessary to make this a book indispensable to all who are interested in petroleum and natural gas.

Even though its shortcomings are so numerous and obvious, the book should be of considerable help to many geologists and engineers interested in the finding and developing of oil and gas fields. Before a second edition is printed it is hoped that the authors will recognize its weak points and will call colleagues to their aid in order that they may be safeguarded from again publishing a volume which requires a trained mind familiar with oil and gas field subjects to even vaguely follow their discussions.

In view of this disappointing volume, it is refreshing to see the appearance of the two-volume work, "The American Petroleum Industry," by Bacon and Hamor, in which Messrs. Johnson and Huntley contributed several chapters. That Messrs. Johnson and Huntley are capable of better writing than their "Principles of Oil and Gas Production" would indicate, is evinced by two of the chapters which they contribute to this more comprehensive and much superior work.

A. E. Fath.

SCIENTIFIC NOTES AND NEWS

DR. CEVELAND ABBE, the distinguished meteorologist, died on October 28, at his home in Chevy Chase, Washington.

W. C. PHALEN has resigned from the U. S. Geological Survey to take up work as mineral technologist in the Bureau of Mines.

DR. J. ERNEST CARMAN, of the University of Cincinnati, has been appointed to the chair of geology at the Ohio State University.

J. B. TYRELL has gone to the East Kootenay district in British Columbia to examine and sample one of the lead-silver mines of that section.

MAX ROESLER, of the Juragua Iron Co., has returned to Santiage after a brief trip to New York.

C. E. VAN BARNEVELD has been appointed superintendent of the Tucson experiment station of the Bureau of Mines.

G. S. RICE, chief mining engineer for the U. S. Bureau of Mines, Washington, D. C., is inspecting the coal mines near Fernie, B. C., for the provincial government of British Columbia.

[1] Geologists, mining engineers and others interested in applied geology are invited to keep the editor informed of new investigations of mining districts or scientific studies undertaken by them, together with such other scientific and personal items as may come to their notice.

INDEX TO VOLUME XI.

[NOTE.—In this index the titles of principal papers and the headings of departments, as *Discussion*, are in italics.]

Abella y Casariego, E., on petroleum in Leyte and Cebu, 246
Adams, F. D., discussion by, 291
Adams, F. D., and Barlow, A. E., on the Glamorgan laccolith, 662
Adams, F. D., and Lawson, A. C., on scapolitic rocks, 678
Adams, L. H., with Johnston, John, *On the measurement of temperature in bore-holes*, 741–762
Adiassevich, A., discussion of paper by, 279
Adularia, 119; association with sericite, 137
Aguila Oil Co., 217
Alamo oil field, 215
Alegria, petroleum, 257
Algoman granite, 233
Alluvial deposits, Beaverhead Range, 711
Alluvial fans, Rocky Mountain province, 712
Allen, E. T., on isometric chalcocite, 12
Allen, E. T., and Crenshaw, J. L., on metacinnabar, 645
Allen, E. T., with Zies, E. G., *Some reactions involved in secondary copper sulphide enrichment*, 407–503.
Almandite, 223
Alsdorf, P. R., *Occurrence, geology and economic value of the pitchblende deposits of Gilpin County, Colorado*, 266–275
Alteration, Clifton-Morenci district, Ariz., 534; of bornite to sulphides of copper, 478; of pyrite to chalcocite, 431; of pyrite to copper-iron sulphides, 454
Alteration products, identifying, 433
Aluminum hydrates in the Arkansas bauxite deposits (Wysor), 42
Aluminum oxide, effect on colloidal suspension, 39
Alumogel, 690
American Geologist, N. H. Winchell and the (Bain), 51
American geology, progress, 51–62
Amphibole, 331
Amphibolites, 330
Anaconda vein, section, 722
Analyses (*see* Chemical Analyses)
Analysis of enrichment products, methods of, 432
Anamorphic changes, 569
Anamorphism, 241
Andradite, 223
Anhydrite, Mound House, Nev., 142
Ansted, D. T., on Maryland copper deposits, 165
Antiquity of man, 68
Apparatus for drilling for oil, 322; used in experimentation on copper minerals, 412
Archæology, The work of N. H. Winchell in glacial geology and (Upham), 63
Archæology, Winchell's writings on, 63
Argentina, oil resources, 313
Argentite, 392
Arkansas bauxite deposits, 686
Arkansas bauxite deposits, Aluminum hydrates in the (Wysor), 42
Arnold, Ralph, *Conservation of the oil and gas resources of the Americas*, 203–222, 299–326; discussion by, 79
Artificial replacement, method of, 365
Ashley, G. H., on ratio of coal to peat, 388
Aspen silver-lead district, Colo., 605
Asphalt, 522
Assay of bonanza ore, 390
Athabasca oil field, 210
Atwood, W. W., *The physiographic conditions at Butte, Montana, and Bingham Canyon, Utah, when the copper ores in these districts were enriched*, 697–740; on glaciation of the Uinta and Wasatch Mountains, 719

Bacterial theory of origin of Chilean nitrates, 106

Bailey, G. E., on origin of Chilean nitrates, 106
Bain, H. F., *N. H. Winchell and the American Geologist*, 51–62; on clay slips, 381; on zinc deposits, 244
Baku oil fields, 279; production, 282
Balakhany oil field, Baku, 279
Baltimore County copper mine, Maryland, 152
Barbados, deposits of petroleum and manjak, 302
Bare Hills copper mine, Maryland, 152
Barite, 635
Barrell, J., on contact action, 552
Bascom, F., on geology of South Mountain region, 172
Bastin, E. S., discussion by, 681; on pitchblende deposits of Gilpin Co., 267; review by, 691
Bauxite, 43; a rock not a mineral, 688; characteristics, 46; chemical analyses, 47 discovery in Arkansas, 42; types in Arkansas, 43
Bauxite deposits, 686
Bauxite deposits, Aluminum hydrates in the Arkansas (Wysor), 42
Bayley, W. S., discussion by, 290; review by, 508
Beaverhead Range, 709; alluvial deposits, 711
Beck, R., on rocks of Broken Hill, N. S. W., 333
Becker, G. F., on propylitic alteration, 560; on the occurrence of quicksilver, 646
Beeson, J. J., monzonite collected by, 120; on sericite in copper ores, 133; petrographic work by, 356
Belt series, 704
Benzene, 517
Bevier coal seam, 382
Bibi-Eibat oil field, Baku, 279
Bibliography—Chilean nitrates, 113; bibliography of sulphide enrichment, 408
Bingham Canyon, Utah, 732; ores, 738; physiographic conditions when the copper ores were enriched, 697, 732
Biotite, analysis, 563
Biotitization, 563
Bischof, C., on the formation of pyrite and marcasite, 597
Bitterroot Valley, 709
Blacktail Canyon, Butte district, 713
Bohemian garnets, 230
Bolivia, oil resources, 312
Bore-hole temperature measurement, 746
Bornite, 158, 163, 170, 349; alteration to sulphides of copper, 478; analyses, 475; constitution, 580; behavior with hydrogen sulphide, 361; replaced by chalcocite, 11; replacing chalcocite, 504
Bornite and calcite, intergrowths, 2
Bornite and chalcocite, relations, 583
Bornite and chalcocite, The so-called graphic intergrowth of (Rogers), 582
Bornite and cupric sulphate, 478; reaction, 474, 480
Bornite and sulphuric acid, 475
Bornite-chalcocite intergrowth, nature and significance, 592
Bornite-chalcocite relations, 179
Boulder batholith, 705
Boutwell, J. M., on physiographic studies in relation to ore deposits, 700
Bownocker, J. A., review of book by, 405
Bozeman beds, 705; distribution, 710
Bradley, H. C., nitro-prusside of sodium test, 339
Branner, J. C., discovery of bauxite in Arkansas, 42; on petroleum prospects of Brazil, 318
Brazil, oil resources, 318
Bréon, René, on separation of minerals, 338
British Columbia, petroleum, 211
Broderick, T. M., *Some experiments bearing on the secondary enrichment of mercury deposits*, 645–651
Broken Hill lode, New South Wales, Observations on the geology of the (Moore), 327
Brower, J. V., archæological monographs by, 70
Building stones of Ohio, 405
Burling, L. D., and Kindle, E. M., on faults in Ontario, 90
Butler, B. S., discussion of paper by, 284; on apically truncated stocks, 572; on sericitization in San Francisco district, Utah, 127
Butler and McCaskey, on copper ores, 173
Butte mining district, Mont., 701; copper from, 586; drainage, 703; Flat, 720; physiographic conditions when the copper ores were enriched, 697; physiographic history, 706; section, 705

Cable for bore-hole temperature measurements, 750
Calcite and bornite, intergrowths, 2

Cage for thermometers in bore-hole measurements, 746
Calgary oil field, 209
Calhoun vein, Gilpin Co., Colo., 273
Calibration of electrical resistance thermometer, 753
Camanchacas, 108
Campeche oil field, Mexico, 222
Canadian oil fields, 206
Cape rubies, South Africa, 230
Capps, S. R., and Leffingwell, E. D. K., on glaciation in the Sawatch Range, 719
Carbonate rocks in the Precambrian, 624
Caribbean district, Colombia, oil resources, 304
Carroll County, Md., copper mines, 152
Carrollite, 155, 157, 161
Cebu, petroleum, 256
Cerro stage of glaciation, 719
Cerussite, 346
Chemical analyses—bauxite, 47; biotite, 563; bornite, 475; chalcopyrite, 464; clay-tuff, Leyte, 261; concretion, Leyte, 261; enrichment products, 432; gabbro, 664; gabbro, "gefleckter," 676; gabbro, scapolitic, 674, 678; magnetite ore, 668; ore, Tyee deposit, 394; pitchblende, 271; quartz monzonite porphyry, 537; rhyolite, Lander Co., Nev., 653; wood tin, 656; zinc concentrate, southwestern Wisconsin, 238; zinc ore, 635
Chemical composition of petroleum, The relation of, to its genesis and geologic occurrence (Mabery), 511
Chalcocite, 123, 158, 163, 170, 349, 352; action of cupric sulphate on, 430; blue and white, 356; conversion to chalcopyrite, 576; derived from pyrite, 431; hypogene origin, 592; intergrowth with bornite, 7; rate of recrystallization, 360; replacement by bornite, 504; two generations, 593; in Virgilina ore, 136
Chalcocite, "sooty," Butte district, 725
Chalcocite, The so-called graphic intergrowth of bornite and (Rogers), 582
Chalcocite and bornite, relations, 583
Chalcopyrite, 158, 163, 170, 349; action of sulphuric acid on, 463; alteration to cupric and cuprous sulphides, 467; behavior with hydrogen sulphide, 361; constitution, 580; discussion of experimental work with, 473; formation by artificial replacement, 574; reaction with cupric sulphate, 463
Chamberlin, T. C., on the loess of Lansing, Kans., 70
Chambers, A. A., analyses by, 652, 656
Channing, J. P., 84
Chelyan, W. Va., bore-hole temperature, 744
Chile, indications of petroleum, 313
Chilean nitrate deposits, The genesis of (Singewald and Miller), 103
"Chloritic" material in ores of southeastern Missouri, 289
Cinnabar, experiments on, 648; from metacinnabar, 646; solubility, 647
Clapp, C. H., on Tyee copper deposit, 390
Clark, J. D., and Menaul, P. L., *The rôle of colloidal migration in ore deposits*, 37–41
Clarke, F. W., on origin of Chilean nitrates, 106; on scapolitic rocks, 677; on sericitization, 138
Clay slips, The origin of (Wilson), 381
Cleland, H. F., review of book by, 598
Clifton-Morenci, The mineralization at (Reber), 528
Clinton iron ores of Appalachian region, 597
Coal, in Bozeman deposits, 712; ratio to peat, 387
Colleges, relation to geology, 51
Collins, H. F., discussions by, 402, 686
Colloidal migration in ore deposits, The rôle of (Clark and Menaul), 37
Colombia, oil resources, 303
Columnar sections, measurement of, 15
Colvocoresses, G. M., discussion by, 189
Comodoro Rivadavia district, Argentina, oil resources, 314
Composition, chemical, of petroleum, The relation of, to its genesis and geologic occurrence (Mabery), 511
Conservation of oil resources, 319
Conservation of the oil and gas resources of the Americas (Arnold), 203, 299
Contact alteration, 569
Contact metamorphism, 552, 554; definition, 555; Long Lake zinc mine, 241
Contact metamorphism at the Long

Lake zinc mine, Ontario, Ore genesis and (Uglow), 231
Contact metasomatism, 552
Continental Divide, 709, 714
Coons, A. B., production of crude petroleum in Peru, 311
Copper, Clifton-Morenci district, Ariz., 532; Frederick Co., Md., character, 170; mode of occurrence, 168; in red beds of New Mexico, 594; production in Maryland, 151; recent literature on, 293
Copper deposit, Tyee, of Vancouver, Island, A peculiar type of ore from (Dolmage), 390
Copper enrichment, relative rate, 496
Copper minerals, sizing, 410
Copper nickel ores, Insizwa range, Africa, 397
Copper ores, enrichment at Butte, Mont., 697; Maryland, 155; Plumas Co., Cal., sections, 122; polished sections, 368; Sierra Oscura, N. Mex., 367
Copper ores of Maryland, A metallographic study of (Overbeck), 151
Copper ores of the "red beds" type, Origin of (Rogers), 366
Copper sulphide enrichment, Some reactions involved in secondary (Zies, Allen and Merwin), 407
Copper sulphides, 349
Corona Oil Co. (Dutch Shell), 217
Costa Rica, oil seepages, 300
Cottonwood-American Fork region, Utah, 284
Covellite, 158, 349; action of cupric sulphate on, 419; behavior with hydrogen sulphide, 363; conversion to chalcopyrite, 576; intergrowth with galena, 10; reaction, 425; natural, experiments on, 423; synthetic, 420
Covellite and cupric sulphate, reaction, 426
Covellite and cuprous sulphate, 427; reaction, 429
Cox, G. H., on lead and zinc ores, 244
Crane, W. R., on clay slips, 382
Crenshaw, J. L., analysis by, 464; on action of cupric sulphate on chalcocite, 430
Cross, W., and Howe, E., on San Juan Mountains, Colo., 607
Cross, W., and Spencer, A. C., on dome structure in Colorado, 607
Cross sections (*see* Sections)
Crude oil in Mexico, production, 218
Crude petroleum, production of, 205
Crystallographic intergrowths, 397
Cuba, petroleum conditions, 301
Cupric sulphate, action on chalcocite, 430; on covellite, 419, 427; on pyrite, 431; reaction with chalcopyrite, 463; with pyrrhotite, 454
Cupric sulphate and bornite, reaction, 474
Cuprous sulphate, action on pyrite, 451

Dacite flows, Butte, Mont., 711
Dallas stage of glaciation, 719
Daubrée, A., on the occurrence of tridymite, 660
Davis, C. A., work of, 403
Day, D. T., on filtration of oils through Fuller's earth, 527
Day, W. C., on distillation of gilsonite, 523
Deer Lodge Valley, alluvial filling, 709
Degree for proficiency in geology, 73
Depth, of ground-water of Chilean pampas, 108; of oil wells in Mexico, 216; of secondary enrichment, Broken Hill district, N. S. W., 344
Derby, A. O., on sericite in the Passagem lode Brazil, 128
Dexter anticline, 276
Diabase, 543
Diabase and basalt dikes, 332
Diagrams—Order of deposition of minerals in tungsten-gold veins, Leadville, Colo., 35; sericitization and propylitization, 566
Diamond fields of southern Africa, 509
Diaspore, 42, 43
Dikes, Gilpin Co., Colo., 269; Navajo Reservation, 228
Diorite porphyry, 538
Discussion—
Aluminum hydrates in the Arkansas bauxite deposits (Fermor), 686
Baku oil fields (Huntley), 279
"Chloritic" material in the ores of southeastern Missouri (Ross), 289
Copper in the red beds of New Mexico (Turner), 594
Copper ores of Maryland (Tolman), 504
Investigation of springs for water supply in Switzerland (Schider), 763
Localization of values or occurrence of shoots in metalliferous deposits (Grout), 395

Occurrence, geology, and economic value of the pitchblende deposits of Gilpin County, Colorado (Bastin), 681
Ores, magmatic emanations and modes of igneous intrusion (Loughlin), 284
Origin and occurrence of certain crystallographic intergrowths (Ray), 179; (Goodchild), 397; (Collins), 402
Origin of certain ore deposits (Uglow), 87
Should a new degree be created for proficiency in geology? (Haworth), 73; (Peele), 77; (Ransome), 77; (Arnold), 79; (Spilsbury), 81; (Ledoux), 83; (Channing), 84; (Norris), 85; (Lawrence), 185; (Tyrrell), 186; (Finch), 187; (Finlay), 188; (Norris), 188; (Colvocoresses), 189; (Willis), 192; (Winchell), 193; (Bayley), 290; Adams, 291
Scientific value of economic geology and double specialization (Lane), 403
Sericite, a low temperature hydrothermal mineral (Tolman), 507
Study of some heating tests (Sosman), 86
Dolly Hyde copper deposit, Md., 167
Dolmage, Victor, *A peculiar type of ore from the Tyee copper deposit of Vancouver Island*, 390–394
Dolores mine, San Luis Potosi, ore-deposition and faulting, 608
Doming, 276
Drainage, Butte region, 703
Drift, thickness in Minnesota, 65
Drilling for oil, apparatus, 322; Cuba, 301
Dutch Guiana, oil resources, 308

East Coast Oil Co. (Southern Pacific), 217
East Ridge, Butte district, 708
Ebano oil field, Mexico, 214, 219
Economic geology. Recent literature on (*see* Recent literature, etc.)
Economic value of the pitchblende deposits of Gilpin County, Colorado. Occurrence, geology and (Alsdorf), 266
Ecuador, oil resources, 309
Editorial, 92
Edwards, N. Y., *The new zinc mining district near* (Newland), 623
Elie rubies, Scotland, 230
Electrical resistance thermometer, 748
Electrical theory of origin of Chilean nitrates, 106
Emmons, E., on the occurrence of zinc ores, 627
Emmons, S. F., on copper deposits, 366; on the Tenmile district, Colo., 606
Emmons, W. H., on deposition at high temperature, 35; on enrichment of sulphide ores, 699; on epidote in contact-metamorphic deposits, 166; on graphic intergrowth of bornite and chalcocite, 175; on mercury minerals, 645; on rhyolites in Nevada, 652
Enargite, 183, 409
Engels mine, Plumas Co., Cal., copper from, 587
Enrichment, Bingham Canyon, 738; Broken Hill district, N. S. W., 344; Butte district, 131, 721, 730; copper, relative rate, 496; copper ores at Butte, Mont., and Bingham Canyon, Utah, physiographic conditions, 697, 732; copper ores, California, 123
Enrichment, Laboratory studies on secondary sulphide ore (Young and Moore), 349, 574
Enrichment, Some reactions involved in secondary copper sulphide (Zies, Allen and Merwin), 407
Enrichment of mercury deposits, Some experiments bearing on the secondary (Broderick), 645
Enrichment products, analysis of, 432
Epidotization, 166
Erosion cycles, Montana and Idaho, 707
Ethylene series, 517
Ettlewood limestone, 330
Eutectic mixtures, 3
Experimental work with chalcopyrite, discussion, 473
Experiments on cinnabar, 648; on manganese solutions, 115; on precipitation of mercury, 648; to determine migration in colloidal condition, 38; with copper sulphides, 350
Experiments bearing on the secondary enrichment of mercury deposits, Some (Broderick), 645
Exploration, in the oil industry, 321

Fath, A. E., on polished sections of copper ore, 366; review by, 764
Faulting, Aspen district, Colo., 605; Leadville district, Colo., 606; Ray

district, Ariz., 612; San Luis Potosi, 608; Tintic district, Utah, 286; Tiro General, San Luis Potosi, 616; Tonopah district, Nev., 614
Faulting, The relation of ore-deposition to (Spurr), 601
Ferberite, 34
Fermor, L. L., discussion by, 686
Ferrous sulphate, influence on reaction between pyrite and cupric sulphate, 448; preparation, 418
Finch, J. W., discussion by, 187
Findlay, Ohio, bore-hole temperature measurements, 747
Finlay, J. R., discussion by, 188
Fitch, R. S., and Loughlin, G. F., *Wolframite and scheelite at Leadville, Colorado*, 30–36
Flat, Butte district, 720
Foothill oil field, 209
Foye, W. G., *The relation of the titaniferous magnetite ores of Glamorgan township, Haliburton County, Ontario, to the associated scapolitic gabbros*, 662–680
Fracture zones, Velardeña district, Durango, 610
Franklin Furnace zinc deposits, 623
Frederick Co., Md., mines, 167
French Guiana, oil seepages, 309
Furbero oil field, 214
Furnace used in experimentation on copper minerals, 414

Gabbro, "gefleckter," 674; composition, 676; Glamorgan, township, Ontario, 662; analysis, 664; scapolitic, 672; composition, 674, 678
Gahnite, 338
Galena, 634; intergrowths with pearcite, 9; secondary, 346
Galena and cupric sulphate, reaction, 492
Garnet deposits on the Navajo Reservation, Arizona and Utah (Gregory), 223
Garnet Ridge garnet field, 226
Garnet rock, 336
Garnet-bearing drift, Utah–Arizona, 227
Garnet-bearing gravels, origin, 228
Garnet-diopside contact rock, 665
Garnets, Navajo Reservation, source, 229
Gas, in the Philippine Islands, 246
Gas resources of the Americas, Conservation of the oil and (Arnold), 203, 299
Gasoline, 516
Gautier, A., guano theory of origin of Chilean nitrates, 105
"Gefleckter" gabbro, 674; composition, 676
Geographic features of Montana and Idaho, 701
Genesis of, certain Canadian ores, 87; copper deposits, 12; Carroll County, Md., copper deposits, 165; Frederick Co., Md., copper deposits, 174; copper ores of "red beds" type, 376; graphic intergrowths, 3; ore bodies of Broken Hill district, N. S. W., 339; ores of southeastern Missouri, 290; wood tin deposits, Lander Co., Nev., 660; zinc ores, Edwards district, N. Y., 642; zinc ores, Long Lake mine, Ontario, 241 (*see also* Origin)
Genesis and geologic occurrence, The relations of the chemical composition of petroleum to its (Mabery), 511
Genesis of the Chilean nitrate deposits (Singewald and Miller), 103
Geologic history, pitchblende deposits, Gilpin Co., Colo., 275
Geologic maps—Clifton quadrangle, Ariz., 530; Glamorgan township, Ontario, 663 (*see also* Maps)
Geologic occurrence, The relations of the chemical composition of petroleum to its genesis and (Mabery), 511
Geologist, American, N. H. Winchell and the (Bain), 51
Geology, Clifton-Morenci district, Ariz., 529; copper mines of Maryland, 153; Edwards district, N. Y., 629; garnet fields, Utah–Arizona, 226; Long Lake zinc mine, 231; Mineral Hill copper mine, Md., 159; New London copper deposit, Md., 172; Oquirrh Range, 734; petroleum of the Philippine Islands, 247; pitchblende deposits of Gilpin Co., 267; Rocky Mountain region, 704; state in 1888, 51; textbooks, 194, 598; western division of Piedmont, Md., 169
Geology and economic value of the pitchblende deposits of Gilpin County, Colorado, Occurrence (Alsdorf), 266
Geology of the Broken Hill lode, New South Wales, Observations on the (Moore), 327
Georgetown silver-lead-zinc district, Colo., 605

Gibbsite, 43, 46, 687; secondary, 49
Gila conglomerate, 612
Gilbert, C. C., and Pogue, G. E., on intergrowths of bornite and calcite, 2
Gilpin County, Colorado Occurrence, geology and economic value of the pitchblende deposits of (Alsdorf), 266
Gilsonite, distillation, 523
Glacial geology and archæology, The work of N. H. Winchell in (Upham), 63
Glaciation, Butte district, 717; supposed, Navajo Reservation, 228
Glamorgan township, Haliburton County, Ontario, The relation of the titaniferous magnetites of, to the associated scapolitic gabbros (Foye), 662
Glauconite, 290
Gneiss, 335
Gold, occurrence at Leadville, Colo., 30; recent literature on, 293
Goodchild, W. H., discussion by, 397
Goode, J. P., on the piracy of the Yellowstone, 716
Gradient, temperature, 741
Granite, 233, 545, 631
Granite porphyry, 534
Granitic bauxite ore, 43
Graphic intergrowths, 3; structure, 6
Graphic intergrowth of bornite and chalcocite, The so-called (Rogers), 582
Graphite gneiss, section, 141
Graton, L. C., acknowledgments to, 700; investigations on copper, 409; on copper ores, 377; on cupriferous formations, 594
Graton, L. C., and Murdoch, J., on intergrowths of bornite and calcite, 2; on secondary chalcopyrite, 158, 163
Gregory, H. E., *Garnet deposits on the Navajo Reservation, Arizona and Utah*, 223–230
Grenville limestones, 625
Grenville series, 630
Gresley, W. S., on clay slips, 381
Grossularite, 223
Ground-water, of Chilean pampas, 108; table, 698
Grout, F. F., discussion by, 395; on influence of surface in experimentation, 410; on solubility of cinnabar, 647
Guano theories of origin of Chilean nitrates, 105
Guatemala, oil resources, 299
Guiana, oil resources, 308
Gypsum, Mound House, Nev., 142

Hager, Dorsey, *The occurrence of the older beds in structural depressions*. 276–278
Haiti, indications of petroleum, 302
Hallock, W., thermometers of, 742
Hamilton, N. F., analysis by, 393
Harder, E. C., review by, 95
Hatch and Corstorphine, on Cape rubies, 230
Haworth, E., discussion by, 73; on sericite associated with topaz, 127
Hayes, A. O., review of work by, 95
Heating tests, 86
Heddle, on Scottish rubies, 230
Hell Gate River, 716
Hess, F. L., on paragenetic relations of scheelite to wolframite, 35
Hess, W. H., on the origin of cave nitrate, 106
Heterostegina margaritata Schlumberger, 248
Hibbs well, temperature measurements. 757
Hickling, on formation of sericite, 146
Highlands, Butte district, 708
Hillebrand, W. F., analysis by, 271
Hillebrand, W. F., and Schaller, W. T., on mercury minerals of Terlingua, 645
Hillinger, C. G., guano theory of origin of Chilean nitrates, 105
History of progress of American geology, 51–62
Holland, Thomas, on bauxite, 45
Holmes, W. H., on evidences of the antiquity of man, 69
Honduras, oil indications, 300
Huasteca oil district, Mexico, 220
Hunter, C. M., on oil conditions in Peru, 309
Huntley, L. G., discussion by, 279
Huntley, L. G., and Johnson, R. H., review of book by, 764
Hussak, E., on the Passagem lode in Brazil, 128
Hydrates, Aluminum, in the Arkansas bauxite deposits (Wysor), 42
Hydrogen sulphide, 349
Hydrometamorphism, defined, 147
Hydrothermal alteration, 552, 560, 569

"Ice-cake" structure in copper ores, 586
Ice sheet, description of, 64
Idaho Springs formation, 267

Identifying alteration products, 433
Igneous activity, 617
Igneous emanation, rôle in ore formation, 92
Igneous intrusion, modes of, 284
Iki, T., on petroleum in Japan, 265
Index of current literature, 598
Insizwa range, 397
Interglacial stage, Minnesota, duration, 67
Intergrowth of bornite and chalcocite, The so-called graphic (Rogers), 582
Intergrowths, sulphide, The paragenesis of certain (Whitehead), 1
Intermontane troughs, Rocky Mountain province, 709
Intrusion phenomena, Cottonwood-American Fork region, Utah, 284; Tintic district, Utah, 286
Iron, Finksburg-Sykesville belt, Maryland, 153; recent literature on, 294
Iron ore, Newfoundland, 95
Irving, J. D., on contact metamorphism at Ouray, 552

Jacquet, J. B., on Broken Hill lode, 327
Johnson, R. H., and Huntley, L. G., review of book by, 764
Johnston, John, and Adams, L. H., *On the measurement of temperature in bore-holes*, 741–762
Jones, R. W., analysis by, 635
Jordan Valley, 737
Judd, J. W., on scapolite, 677

Kaolinite, 689
Katamorphic changes, 569
Kedabekose, 665
Kemp, J. F., on use of term propylite, 560
Kerosene, 516
Keyes, C. R., on clay slips, 381
Kindle, E. M., and Burling, L. D., on faults in Ontario, 90
Kirk, C. T., on hydrothermal origin of sericite, 149; on sericite at Butte, Mont., 130
Klaprothite, 583, 585
Knopf, Adolph, *Wood tin in the Tertiary rhyolites of northern Nevada*, 652–661; on apatite in altered albite-diorite, 129; on lead-tourmaline type of veins, 127
Koenigsberger, J., and Müller, W. J., on the formation of silicates, 660; on higher temperature gradient as indication of coal or oil, 741

Laboratory studies on secondary sulphide ore enrichment (Young and Moore), 349, 574
Laccolith, Glamorgan, 662
Lacroix, A., on bauxite, 45, 687; on scapolite, 677
Lake Bonneville, 733
Lane, A. C., discussion by, 403
Laney, F. B., on graphic intergrowth, 582, 583; on intergrowths of bornite and calcite, 1; on Virgilina ores, 135
Lansing skeleton, 69
Lapparent, A. de, on sericite in metamorphic rocks, 139
Lava, Snake River region, 711
Lawrence, B. B., discussion by, 185
Lawson, A. C., on Algoman granite, 233
Leadville, Colo., ore-deposition and faulting, 606
Leavenworth sulphide vein, Gilpin Co., Colo., 274
Ledoux, A. R., discussion by, 83
Leith, C. K., on micaceous quartzite from Hoosac Tunnel, 143; on the metamorphic cycle, 569
Lenher, V., *The oxidation of manganese solutions in the presence of the air*, 115–117
Leyte, petroleum, 250, 257
Liberty copper mine, Md., 168
Liesegang, R. E., on banding, 657; on brecciated agates, 659
Limestone, 548; crystalline, 232; effect on colloidal suspension, 39
Lindgren, W., on Clifton-Morenci district, 528; on copper deposits, 366; on copper ores of Red Gulch, Colo., 376; on enrichment of Butte ores, 730; on formation of sericite, 146; on hydrothermal origin of sericite, 149; on propylitization, 561; on relation of ore deposition to physical conditions, 36; on sericite, 118; on sericite in Nevada Co., Cal., 128; on the formation of pyrite and marcasite, 597; on the origin of cinnabar, 645
Lindgren, W., and Ransome, F. L., on sericite and adularia in Cripple Creek ore, 137
Linganore mine, Md., 171
Liquation of sulphides, 401
Literature, Recent, on economic geology (*see* Recent literature, etc.)
Lithomarge, 689
Lithothamnium ramosissimum Reuss, 249

Little Prickly Pear creek, piracy of, 716
Lobitos oil field, Peru, 311
Localization, of Chilean nitrates, 104; of values in metalliferous deposits, 395
Long Lake limestone, 241
Long Lake zinc mine, location, 231
Long Lake zinc mine, Ontario, Ore genesis and contact metamorphism at the (Uglow), 231
Lorrain granite, 233
Loughlin, G. F., discussion by, 284; on sericite in alaskite, 139
Loughlin, G. F., with Fitch, R. S., *Wolframite and scheelite at Leadville, Colorado*, 30–36
Lussatite, 653

Mabery, C. F., *The relations of the chemical composition of petroleum to its genesis and geologic occurrence*, 511–527
Macuspana-Chiapas oil field, Mexico, 221
Magdalena-Santander district, Colombia, oil resources, 306
Magmas and faulting, 618
Magmatic contributions to contact metamorphic rocks, 557
Magnetite, 155, 161; relation to sulphides, 505
Magnetites of Glamorgan township, Haliburton County, Ontario, to the associated scapolitic gabbros, The relation of the titaniferous (Foye), 662
Mallard, E., on lussatite, 653
Manganese solutions, The oxidation of, in the presence of air (Lenher), 115
Mannington, W. Va., bore-hole temperature measurements, 755
Mansfield, G. R., review by, 194
Mapping width of a formation, 16
Maps—Bozeman beds, Montana–Idaho, 710; Edwards district, N. Y., 628; garnet deposits, Utah–Arizona, 225; Philippine Islands, 246; piracy of the Missouri, 715 (*see also* Geologic maps)
Marl deposits, origin, 403
Marsh gas, 516
Matehuala, San Luis Potosi, ore-deposition and faulting, 608
Mathews, E. B., and Grasty, J. S., on limestones of Maryland, 169
Mawson, D., on Broken Hill area, 327
Mayflower vein, Gilpin Co., Colo., 273
Mead, W. J., on bauxite, 45
Measurement of temperature in bore-holes, On the (Johnston and Adams), 741
Melaconite, 373
Melville, W. H., on metacinnabar in the New Almaden mines, 646
Menaul, P. L., with Clark, J. D., *The rôle of colloidal migration in ore deposits*, 37–41
Mendoza-Neuquen district, Argentina, oil resources, 316
Mennell, on bornite in Mashonaland, 379
Mercury, chemistry, 646; precipitation of, 648
Mercury deposits, Some experiments bearing on the secondary enrichment of (Broderick), 645
Mercury thermometer, use in bore-hole measurement, 742
Merwin, H. E., with Zies, E. G., *Some reactions involved in secondary copper sulphide enrichment*, 407–503
Metallographic study of the copper ores of Maryland (Overbeck), 151
Metamorphic cycle, 569
Metamorphism, distinction between contact and hydrothermal, 570; static, 147
Metasomatic graphic intergrowth, 9
Metasomatism, 341, 552
Meteoric waters, agency in formation of "red beds" type of copper ores, 380; rôle in ore formation, 92
Method of artificial replacement, 365; of conservation of oil resources, 319
Mexican crude oil, use, 216
Mexican Petroleum Co., Ltd., 217
Mexico, petroleum, 212
Mica rock, 540
Micro-drawings, pitchblende ore, 682; zinc ore, 638
Micro-pegmatite, 541
Microphotographs (*see* Photomicrographs)
Microscopical determination of opaque minerals, review of, 691
Migration in ore deposits, The rôle of colloidal (Clark and Menaul), 37
Miller, B. L., with Singewald, J. T. Jr., *The genesis of the Chilean nitrate deposits*, 103–114
Miller, W. G., and Knight, C. W., on pre-Cambrian of Ontario, 232
Mindoro, gas, 255
Mineral deposits (*see* Ore deposits)
Mineral Hill copper mine, Maryland, 152, 159

Mineralization, Clifton-Morenci district, Ariz., 533; definition, 533; Ray district, Ariz., 613
Mineralization at Clifton-Morenci, (Reber), 528
Minerals, colloidal dispersion of, 39; determination of, 691; in bauxite, 48; of an ore deposit, successive formation, 138
Mining geologist, 73
Mining World index of current literature, 598
Mississippi River, preglacial course, 68
Missouri River, piracy of, 714
Modes of igneous intrusion, 284
Moira granite, 233
Monadnocks, Montana, 708
Monzonite porphyry, 535
Moore, E. S., *Observations on the geology of the Broken Hill lode, New South Wales*, 327–348
Moore, N. P., with Young, S. W., *Laboratory studies on secondary sulphide ore enrichment*, 349–365, 574–581
Moraines, Butte district, 717
Morey, G. W., Jr., on a method of closure, 415
Morse, W. C., review by, 405
Moses Rock garnet field, 226
Motembo, Cuba, oil well, 301
Mountain Lake mine, Utah, copper from, 583
Mountain View lead mine, Md., 168
Mule Ear garnet field, 224
Müntz, A., on formation of Chilean nitrates, 106
Murdoch, Joseph, on the microscopical determination of opaque minerals, 426; review of book by, 691
Muscovite, relations to sericite, 119

Nacimiento district, N. Mex., copper ores, 374
Naphtenes, 517
Navajo Reservation, Arizona and Utah, Garnet deposits on the (Gregory), 223
Negritos oil field, Peru, 312
Nevada Creek, 716
New zinc mining district near Edwards, N. Y., The (Newland), 623
New Brunswick, petroleum, 207
Newfoundland, petroleum of, 206
Newland, D. H., *The new zinc mining district near Edwards, N. Y.*, 623–644
New London mine, Md., 171; type of deposit, 173
Newton, William, on bacterial theory of origin of Chilean nitrates, 106
New Windsor copper deposit, Md., 167
News (*see* Scientific notes and news)
Nickles, J. M., review by, 598
Nishihara, G. S., on rate of enrichment activity, 493
Nitrate deposits, Chilean, The genesis of (Singewald and Miller), 103
Noellner, C. N., seaweed theory of origin of Chilean nitrates, 104
Nomograph, accuracy of, 27; rules for, 18
Nomographic solutions of certain stratigraphic measurements (Palmer), 14
Norris, R. V., discussions by, 85, 189
Northern Ore Co., 627
Northwest Territories, petroleum, 210
Notes (*see* Scientific notes and news)
Nova Scotia, petroleum, 207
Nummulites niasi Verb., 248

Observations on the geology of the Broken Hill lode, New South Wales (Moore), 327
Occurrence, geology and economic value of the pitchblende deposits of Gilpin County, Colorado (Alsdorf) 266
Occurrence of older beds in structural depressions (Hager), 276
Occurrence of petroleum in the Philippines (Pratt), 246
Ochsenius, C., guano theory of origin of Chilean nitrates, 105
Oehmichen, on Bohemian garnets, 230
Oil, recent literature on, 295 (*see also* Petroleum)
Oil and gas production, principles of, 764
Oil and gas resources of the Americas, Conservation of the (Arnold), 203, 299
Oil fields, of Mexico, 212; of North America, 206; of the United States, 211
Oil shales, Brazil, 318
Oklahoma, structural domes, 276
Oligocene, Philippine Islands, 247
On the measurement of temperature in bore-holes (Johnston and Adams), 741
Ontario, ore deposits, 88; petroleum, 206, 208
Ookiep magmatic ores, 126
Oolitic bauxite ore, 43
Opal, 656

Oquirrh Mountains, 732; geology, 734
Ore deposition, a catastrophic phenomenon, 604; conditions, 620; methods of, 573
Ore-deposition, The relation of, to faulting (Spurr), 601
Ore-deposition and intrusions, 619
Ore deposits, Bingham Canyon, 738; diverse origin, 601; formation by colloidal action, 41
Ore deposits, The rôle of colloidal migration in (Clark and Menaul), 37
Ore enrichment, Laboratory studies on secondary sulphide (Young and Moore), 349, 574
Ore genesis and contact metamorphism at the Long Lake zinc mine, Ontario (Uglow), 231
Ore shoots in metalliferous deposits, 395
Origin of, Butte district ores, 721; certain Canadian ore deposits, 87; Chilean nitrate deposits, 103; clay slips, 384; garnet-bearing gravels, 228; mineralizing solutions, 571; scapolitic rocks, 677; titaniferous iron ore deposits, 679 (*see also* Genesis)
Origin of clay slips (Wilson), 381
Origin of copper ores of the "red beds" type (Rogers), 366
Osborne, C. B., on oil prospects in Cuba, 301
Overbeck, R. M., *A metallographic study of the copper ores of Maryland*, 151–178
Oxidation of manganese solutions in presence of the air (Lenher), 115
Oxidation zone, Butte district, 727

Pacific district, Colombia, oil resources, 306
Paige, Sidney, on origin of sericite in a Burro Mountains deposit, 146
Paleoliths of Kansas, 71
Palla, on the formation of marcasite, 597
Palmer, H. S., *Nomographic solutions of certain stratigraphic measurements*, 14–29
Panama, oil resources, 300
Panay, gas and petroleum, 256
Pangasinan, petroleum, 252
Panuco-Topila oil field, Mexico, 219
Paraffine oils, 516
Paragenesis, 393, 556; Broken Hill district, N. S. W., 340; copper minerals, 371; Leadville ores, 34; Long Lake zinc mine, 236; opaque minerals of Patapsco mine, 159, 163; zinc ore, 637
Paragenesis of certain sulphide intergrowths (Whitehead), 1
Pardee, J. T., on alluvial filling in Montana, 709
Patapsco mine, Finksburg, Carroll County, Md., 152, 153
Pauls, M., on alumogel, 690
Payne Co., Okla., copper ores, 375
Pearcite, intergrowths with galena, 9
Peat, ratio to coal, 387
Peat bog, original thickness, 386
Peat deposits, 404
Peculiar type of ore from the Tyee copper deposit of Vancouver Island (Dolmage), 390
Peele, R., discussion by, 77
Pegmatites, 332
Peneplain, Summit, 707
Pennsylvania Mexican Fuel Oil Co. (Standard Oil), 217
Penrose, R. A. F., Jr., guano theory of origin of Chilean nitrates, 105
Pentlandite, 399
Perry, E. H., acknowledgments to, 700, 732
Peru, oil resources, 309
Petrography, Broken Hill lode, 330
Petroleum, Canada, 206; differentiation of varieties, 525; inorganic theory of origin, 512; need of large-scale investigation, 511; Newfoundland, 206; nitrogenous ingredients, 513, 526; Ontario, 208; organic origin, 526; Philippines, character, 262; Philippines, commercial possibilities, 263; sulphur in, 519; table of production, 205 (*see also* Oil)
Petroleum, The relations of the chemical composition of, to its genesis and geologic occurrence (Mabery), 511
Petroleum in the Philippines, The occurrence of (Pratt), 246
Petrology Clifton-Morenci district, Ariz., 532
Philippines, The occurrence of petroleum in the (Pratt), 246
Photomicrographs—artificial replacements, 578; altered granite or monzonite porphyry, 536; copper ores, 132; copper ores, Butte, Mont., 180, 184; copper ore, Maryland, 156, 162, 164; Sierra Oscura copper ores, 368, 370; copper ore from Virgilina district, 136; covellite, chalcocite, and bornite, 578; diabase, 542, 546; graphic inter-

growths of copper minerals, 584, 588, 590; intergrowth of rutile and titanite, 337; magmatic copper ores, 122, 124; magnetite ore, 670; mica rock, 536, 542; micropegmatite, 542; pitchblende ore, 684; replacement of calcite by sulphides, 392; sericitized quartzite, 546; wood replacement ores, 372
Physiographic conditions, Bingham Canyon, Utah, 732
Physiographic conditions at Butte, Montana and Bingham Canyon, Utah, when the copper ores in these districts were enriched (Atwood), 697
Physiographic control of enrichment, 731
Physiographic history, Butte district, 706
Physiography, Oquirrh Range, 735
Piracy, of Little Prickly Pear Creek, 716; of the Missouri, 714
Pirsson, L. V., on magmatic action, 91; review of book by, 194
Pitchblende, 271
Pitchblende deposits, 681
Pitchblende deposits of Gilpin County, Colorado, Occurrence, geology and economic value of the (Alsdorf), 266
Plagemann, A., on origin of Chilean nitrates, 106
Pogue, G. E., and Gilbert, C. C., on intergrowths of bornite and calcite, 2
Polished sections of copper ores, 368
Polymorphism, 119
Pope, F. J., analysis by, 668
Porphyry, Clifton-Morenci district, Ariz., 532
Porto Rico, petroleum indications, 302
Postglacial time, duration, 67
Potash, recent literature on, 296
Pratt, W. E., *The occurrence of petroleum in the Philippines*, 246–265
Pre-Cambrian limestone, origin, 404
Pre-Cambrian rocks at Broken Hill, N. S. W., 329
Pre-Wisconsin glaciation, Butte district, 717; Rocky Mountain province, 719
Primary and secondary minerals, use of terms, 504
Progress of American geology, 51–62
Propylitization, 560
Pusey iron mine, 667
Pyridine, 521
Pyrite, 32; action of cupric sulphate on, 431; cuprous sulphate on, 451; alteration to chalcocite, 431; to copper-iron sulphides, 454; to cupric and cuprous sulphides, 438; formation of, 379
Pyrite and cupric sulphate, 438; reaction, 440, 448
Pyrolusite, deposition of, 115
Pyrope, 223, 224
Pyrrhotite, reaction with cupric sulphate, 454
"Pyrrhotite bridges," 575

Quartz, 32
Quartzite, 334, 550
Quaternary formations, Butte district, 705
Quebec, petroleum, 207; ore deposits, 88

Radium, 266
Rafaelite, 317
Rainfall, Utah, 733
Ramany oil field, Baku, 279
Ransome, F. L., discussion by, 77; on the Silverton district, Colo., 607
Ratio of peat to coal, 387
Ray, J. C., discussion by, 179; on intergrowths of bornite and calcite, 2; on sericite at Butte, Mont., 130
Ray copper district, Ariz., mineralization and deformation, 612
Reaction between chalcopyrite and cupric sulphate, 463; cupric sulphate and bornite, 474; galena and cupric sulphate, 492; pyrrhotite and cupric sulphate, 454; sphalerite and cupric sulphate, 486; mercurous chloride, 650
Reaction rims, 670
Reactions involved in secondary copper sulphide enrichment, Some (Zies, Allen and Merwin), 407
Reber, L. E., Jr., *The mineralization at Clifton-Morenci*, 528–573
Recent literature on economic geology (Paige), 293
Red Gulch, Colo., copper ores, 375
Red Mountain, Butte district, 708
Relation of ore-deposition to faulting (Spurr), 601
Relation of the titaniferous magnetite ores of Glamorgan township, Haliburton County, Ontario, to the associated scapolitic gabbros (Foye), 662
Relations of the chemical composition of petroleum to its genesis and geologic occurrence (Mabery), 511

Relief map—Montana-Idaho-Wyoming, 702
Replacement, artificial, 365; by volumes, 558; of bornite by chalcocite, 9; of chalcocite by bornite, 181, 504; rate of, 577
Resistance thermometer, 749; calibration, 753
Reticulate intergrowths, 10
Reviews—
Building stones of Ohio (Bownocker), Morse, 405
The diamond fields of southern Africa (Wagner), Schaller, 508
Geology, physical and historical (Cleland), Bayley, 598
Microscopical determination of the opaque minerals (Murdoch), Bastin, 691
The Mining World index of current literature (Sisley), Nickles, 598
Principles of oil and gas production (Johnson and Huntley), Fath, 764
A textbook of geology (Pirsson and Schuchert), Mansfield, 194
Wabana iron ore of Newfoundland (Hayes), Harder, 95
Rhodolite, 223
Rhodonite, 335
Rhyolite flows, Butte, Mont., 711
Rickard, Forbes, on pitchblende mineralization, 681; on the German-Belcher-Wood deposits, 270
Rims, reaction, 670
Rocky Mountain province, uplift, 708
Rogers, A. F., *Origin of copper ores of the "red beds" type*, 366–380; *Sericite, a low temperature hydrothermal mineral*, 118–150; *The so-called graphic intergrowth of bornite and chalcocite*, 582–593; on intergrowths of bornite and chalcocite, 2; on sulphide enrichment of copper ores, 175; on two generations of chalcocite, 593
Rôle of colloidal migration in ore deposits (Clark and Menaul), 37
Ross, C. S., discussion by, 289; note by, 594
Rules for nomograph, 18
Russell, I. G., on the Malaspina glacier, 64
Rutherford, E., and Boltwood, B. B., on radium, 266
Rutile, 337

Sabunchy oil field, Baku, 270
Salars, 109
Sales, R. H., on chalcocite at Butte, Mont., 593; on localized currents, 396; on ore deposits at Butte, Mont., 179, 700, 721
Salisbury, R. D., on glaciation in the Bighorn Range, 719
Salt, recent literature on, 296
Salta-Jujuy district, Argentina, oil resources, 315
San Cristobal oil field, Mexico, 221
San Felipe series, 213
San Juan region, Colo., ore-deposition and faulting, 606, 608
San Lorenzo Range, Durango, ore-deposition and faulting, 610
San Rafael vein, El Oro, Mexico, 616
Savage, T. E., on clay slips, 382
Scapolite, 670
Schaller, W. A., review by, 508
Scheelite, 34
Scheelite and wolframite at Leadville, Colorado (Fitch and Loughlin), 30
Schider, R., discussion by, 763
Schist, Finksburg-Sykesville belt, Maryland, 154
Schmitz, E. J., on siderite in ores near Archer City, Tex., 374
Schrader, F. C., on Nacimiento deposits, 375
Schuchert, Charles, review of book by, 194
Scientific notes and news, 101, 201, 298, 406, 510, 600, 695,
Scotland beds, 302
Seaweed theory of origin of Chilean nitrates, 104
Secondary alteration of ore deposits, relation to evolution of surface, 699
Secondary copper sulphide enrichment, Some reactions involved in (Zies, Allen and Merwin), 407
Secondary enrichment, Broken Hill district, N. S. W., 344; Butte district, 721
Secondary enrichment of mercury deposits, Some experiments bearing on (Broderick), 645
Secondary ores, late formation of, 732
Secondary reactions in experiments on pyrite and cupric sulphate, 445
Secondary sulphide ore enrichment, Laboratory studies on (Young and Moore), 349, 574
Sections, Bingham Canyon, Utah, 739; Butte district, 705; Butte ore deposits, 722; Clifton-Morenci district, Ariz., 531; Green's Mountain, Glamorgan township, Ontario, 666

Segall, J., on bornite-chalcocite ore, 2; on crystallographic intergrowths, 175
Semper, on the origin of Chilean nitrates, 106
Sericite, associated with contact metamorphic ores, 127; with magmatic ores, 121; from Bingham, Utah, 133; from Butte, Mont., 130; from Ely, Nev., 134; from Tuolumne Co., Cal., 130; from Virgilina district, 134; hydrothermal origin, 149; hypogene origin, 593; in deposits formed at intermediate depths, 129; in deposits formed near the surface, 137; in high temperature veins, 127; in metamorphic rocks, 138, 141; in schistose gypsum, 142; occurrence, 120, 121; optical properties, 120; product of weathering, 146; properties, 119; relations to muscovite, 119; to sulphides, 506; temperature of formation, 507
Sericite a low temperature hydrothermal mineral (Rogers), 118
Sericitization, 139, 561
Seven Devils district, Idaho, copper from, 589
Shale, 547
Siderite, 374
Sierra del Fraile, San Luis Potosi, ore-deposition and faulting, 608
Sierra Oscura copper ores, 366; origin, 378
Sillimanite, 329
Silverbow Creek, 711
Silver Peak, Nev., sericitization, 126
Silverton district, Colo., faulting, 607
Singewald, J. T., Jr., and Miller, B. L., *The genesis of the Chilean nitrate deposits*, 103–114
Sisley, G. E., review of book by, 598
Sizing of copper minerals, 410
Slavik, F., on probable identity of lussatite and tridymite, 655
Slips, clay, The origin of (Wilson), 381
Sloughing of chalcocite, 356
Smith, W. D., on Jurassic in Philippine Islands, 247
Smyth, C. H., Jr., on scapolitic gabbro, 677; on the Rossie lead veins, 642
Snake River drainage, 716
So-called graphic intergrowth of bornite and chalcocite (Rogers), 582
Solutions of certain stratigraphic measurements, Nomographic (Palmer), 14
Some experiments bearing on the secondary enrichment of mercury deposits (Broderick), 645
Some reactions involved in secondary copper sulphide enrichment (Zies, Allen and Merwin), 407
Sosman, R. B., discussion by, 86
Soto la Marina oil field, Mexico, 218
South Tuxpam oil field, Mexico, 221
Specularite, 157, 378
Spencer, A. C., on alteration of pyrite, 452
Spessartite, 223
Sphalerite, 157, 161
Sphalerite and cupric sulphate, reaction, 486
Spilsbury, E. G., discussion by, 81
Spurr, J. E., *The relation of ore-deposition to faulting*, 601–622; on adularia and sericite at Tonopah, 137; on alaskite, 126; on contact metamorphism, 554; on fluorine needed for formation of sericite, 149; on glauconite in Missouri, 594; on ore deposition, 573
Statistics, petroleum production, 205
Steidtmann, E., on hydrothermal origin of sericite, 149
Sterrett, D. B., on the Garnet Ridge field, 227
Stewart, C. A., on sericitization at Silverbell, Ariz., 127
Stokes, H. N., on action of cupric sulphate on chalcocite, 430; on reaction of covellite and cupric sulphate, 419
Storage of oil, 324
Stratigraphic measurements, Nomographic solutions of certain (Palmer), 14
Structural depressions, Occurrence of older beds in (Hager), 276
Studies on secondary sulphide ore enrichment, Laboratory (Young and Moore), 349, 574
Sulphide enrichment, Some reactions involved in secondary copper (Zies, Allen and Merwin), 407
Sulphide intergrowths, The paragenesis of certain (Whitehead), 1
Sulphide ore enrichment, Laboratory studies on secondary (Young and Moore), 349, 574
Sulphide veins bearing gold and silver, Gilpin Co., Colo., 273
Sulphides, colloidal, 37
Sulphur, in petroleum, 519
Sulphuric acid, action of chalcopyrite on, 463; influence on pyrite-cupric sulphate reaction, 442

Summit peneplain, 707
Surprise Creek, Plumas Co., Cal., copper from, 591
Surveys for oil development, 321
Switzerland, investigation of springs for water supply, 763
Synthesis of copper sulphides, 350
Synthetic covellite, 420

Tables—colloidal suspension of minerals, 39–41; Colombia oil districts, 304; fractional distribution of Philippine petroleums, 262; Mexican oil wells, production, 215; oil resources of the Americas, 319; oolitic bauxite ore, 45–50; operating companies and well data, Mexico, 216; production of crude oil in Mexico, 218; in Comodoro Rivadavia field, Argentina, 315; in Peru, 311; production of petroleum in Ontario, 209; reactions of copper minerals, 421–498; synthetic covellite and cupric sulphate, 421; temperature measurements in bore-hole near Chelyan, W. Va., 744; at Findlay, Ohio, 747; near Mannington, W. Va., 755; world's production of crude petroleum, 205
Talc deposits, Edwards district, N. Y., 628
Tamasi oil field, Mexico, 218
Tamasopo limestone, 213
Tampico oil fields, 214
Tar Sand oil field, 210
Tarapacá nitrate field, 109
Tarr, W. A., on copper ores from Payne Co., Okla., 375
Tayabas, geology, 253; petroleum, 251, 253
Temperature in bore-holes, On the measurement of (Johnston and Adams), 741
Tenmile district, Colo., ore-deposition and faulting, 606
Tetrahedrite in sericitic quartzite, Mullan, Idaho, 141
Tetrahydrochinoline, 521
Textbook of geology, 194
Thermometer, electrical resistance, 748; mercury, use in bore-hole measurement, 742
Thiophane, 521
Thompson, Beeby, on Baku oil fields, 281
Timber Butte, 712
Tin, Wood, in the Tertiary rhyolites of northern Nevada (Knopf), 652
Tintic district, Utah, 286
Tiro General, San Luis Potosi, faulting, 616
Titania in bauxites, 689
Titaniferous magnetites of Glamorgan township, Haliburton, County, Ontario, to the associated scapolitic gabbros, The relation of the (Foye) 662
Titicaca oil field, Peru, 312
Titles to petroleum land, 319
Tobler, August, on petroleum in Sumatra, 265
Tolima district, Colombia, oil resources, 307
Tolman, C. F., Jr., discussions by, 504, 506; on low temperature origin of sericite, 146
Tonopah district, Nev., mineralization and deformation, 61
Topila oil field, 215
Topography of Montana and Wyoming, 701
Torrowangee tillites, 329
Tovote, W. L., on geology of Clifton-Morenci district, 532
Transportation and storage of oil, 324
Trap, 631
Tridymite, 656
Trinidad, oil resources, 301
Tubara oil field, Colombia, 305
Turbaco oil field, Colombia, 305
Turner, H. W., copper ores collected by, 367; discussion by, 594; on the geology of the Sierra Oscura copper deposits, 367
Tyee copper deposit of Vancouver Island, A peculiar type of ore from (Dolmage), 390
Tyrrell, J. B., discussion by, 187
Tyson, P. T., on copper ore in Maryland, 154

Uglow, W. L., *Ore genesis and contact metamorphism at the Long Lake zinc mine, Ontario*, 231–245; discussion by, 87; on Long Lake zinc mine, 623
Umpleby, J. B., on an ancient drainage system in Idaho, 709, 716; on sericite and adularia 138; on sericite at Mackay, Idaho, 127; on the old erosion surface in Idaho, 701
Underground water (*see* Groundwater)
Universities, relation to geology, 51
Upham, Warren, *The work of N. H. Winchell in glacial geology and archæology*, 63–72
Uraninite, 271, 684
Utilization of oil, 325

Valles (San Pedro) oil field, Mexico, 220

Vancouver Island, A peculiar type of ore from the Tyee copper deposit of (Dolmage) 390
Van Hise, C. R., classification of metamorphic changes, 569; on ore deposition, 380
Van Orstrand, C. E., temperature measurements, 756
Van't Hoff, on effect of heat on gypsum, 144
Velardeña district, Durango, ore-deposition and faulting, 610
Vicarya callosa Jenk., 249
Virgilina district, copper ores from, 589

Wabana iron ore of Newfoundland, 95
Wagner, P. A., review of book by, 508
Warping, western Montana, 707
Warren, C. H., on reaction rims, 672
Washburne, C. W., on estimation of oil reserves, 280
Water, recent literature on, 297
Waters-Pierce Co. (Standard Oil), 217
Weber grit, 31
Weed, W. H., on genesis of Frederick Co., Md., copper ores, 174; on geology of the Butte district, Mont., 700; on Maryland copper deposits, 165; on sericite at Butte, Mont., 130; on Tyee copper deposit, 390
Wherry E. T., on nomenclature of colloidal forms of minerals, 690
White, David, on common origin of coal and petroleum, 514; on ratio of coal to peat, 388
Whitehead, W. L., *The paragenesis of certain sulphide intergrowths*, 1–13
Whitman, A. R., on meteoric origin of a pyrite deposit, 379
Williams, G. H., on sericitization, 139
Willis, Bailey, discussion by, 192
Willis, Bailey, and Smith, G. O., on glaciation in the Cascade Mountains, 719
Willyama Complex, 329
Wilson, W. B., *The origin of clay slips*, 381–389
Winchell, H. V., discussion by, 193; on alteration of pyrite, 452
Winchell, N. H., portrait, 63
Winchell, N. H., and the American Geologist (Bain), 51
Winchell, N. H., The work of, in glacial geology and archæology (Upham), 63
Wisconsin stage, Butte district, 720
Wolframite, 33
Wolframite and scheelite at Leadville, Colorado (Fitch and Loughlin), 30
Wood tin, analysis, 656
Wood tin in the Tertiary rhyolites of northern Nevada (Knopf), 652
Woods sulphide vein, Gilpin Co., Colo., 274
Woodworth, J. B., on Bozeman beds in Tobacco Root Mountains, 714
Work of N. H. Winchell in glacial geology and archæology (Upham), 63
Wright, F. E., on quartz of the Broken Hill area, N. S. W., 343
Wysor, D. C., *Aluminum hydrates in the Arkansas bauxite deposits*, 42–50

Yellowstone River, 716
Yoshimura, Manji, experiments on chalcocite, 357
Young, S. W., and Moore N. P., *Laboratory studies on secondary sulphide ore enrichment*, 349–365, 574–581

Zies, E. G., Allen, E. T., and Merwin, H. E., *Some reactions involved in secondary copper sulphide enrichment*, 407–503
Zinc, Broken Hill district, N. S. W., 327; Franklin Furnace, 623; in Precambrian rocks, 623; recent literature on, 294
Zinc mining district near Edwards, N. Y., The new (Newland), 623
Zinc ore, analysis, 635; Long Lake mine, Ont., 231
Zinc spinel, 338
Zones, contact (*see* Contact metamorphism)
Zorritos oil field, Peru, 311

C15